A STUDY ON THE BEHAVIOR OF RC BEAMS PROVIDED WITH WELDED WIRE MESH AS A CORE ZONE REINFORCEMENT

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In

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by

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CERTIFICATE

This is to certify that the thesis entitled "**A STUDY ON BEHAVIOUR OF RC BEAMS PROVIDED WITH WELDED WIRE MESH AS CORE ZONE REINFORCEMENT**" being submitted by **MRS CH. MANJULA** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the faculty of Engineering and Technology of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by her under my supervision and it has not been submitted elsewhere for award of my degree.

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DECLARATION

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ABSTRACT

It is a known fact that the Reinforced Concrete (RC) due to its inherent advantages, occupies a prominent place among several materials used in building construction. While carrying the different building loads the reinforced concrete members are subjected to flexure, shear and torsional affects. In the design of concrete structures, it is generally desirable to ensure that ultimate strengths are governed by flexure rather than shear. Hence from the point of structural safety, the RC members are designed primarily to flexure and are normally engineered to fail in flexure rather than in shear at ultimate. This is because the shear failures are characterized by sudden and brittle in nature compared to the ductile modes of failure due to flexure. Shear failures, which in reality are failures under combined shear forces and bending moments, are characterized by small deflections and lack of ductility. Several research studies conducted in the past have investigated about the factors affecting shear failure and developed numerous models, theories and designs to understand the same.

For resisting different loads, the RC members are normally reinforced with both longitudinal and transverse reinforcement to take care of flexure and shear respectively. The resistance to shear in RC members is in general contributed by (i) Shear strength of concrete and (ii) Shear strength due to transverse reinforcement. The different types of reinforcement used for resisting shear in RC members include bent up / cranked bars, transverse reinforcement in the form of vertical or inclined stirrups. The bent-up bar capacity towards shear resistance in RC members is in general limited due to their in-effectiveness in the event of load reversals.

In general, the Reinforced concrete (RC) beams subjected to transverse loading create non-uniform bending accompanied by internal shear forces. With the result the Reinforced concrete beam cross-section experiences the normal and flexural shear stresses. In homogeneous rectangular cross sections, the intensity of flexural shear stress becomes zero in the outer edges and reaches maximum at the neutral axis i.e., near the core zone of the cross-section

The stirrups go around near to the periphery. This kind of placement of stirrups in reinforced concrete beams leaves the core of the cross section where there is existence of high transverse stress (shear stress), unreinforced. At present, the RC beams are provided with rectangular stirrups (having required diameter, spacing and number of vertical legs) for resisting shear force. Further the stirrups provide resistance against diagonal tension due

to shear only in discrete manner. This leads to sudden appearance and propagation of cracks, leading to brittle failures under shear. Hence, a hypothesis is made that by providing any form of effectively anchored reinforcement in the core zone that intersects these shear cracks will improve the performance of RC members under the influence of transverse stresses. Keeping the hypothesis in mind, a novel means of resisting shear and simultaneously improving the performance of reinforced concrete members by using a prefabricated mesh such as Welded Wire Mesh (WWM) as a core zone reinforcement is presented in this investigation. In this investigation, the welded wire mesh is used either as transverse reinforcement replacing totally the conventional stirrups or as longitudinal core reinforcement apart from conventional rectangular stirrups /ties to resist against diagonal tension due to shear.

An experimental and numerical investigation was carried out in **four** different phases to ascertain the efficacy of the core zone reinforcement in the form of Welded Wire Mesh (WWM) used either as transverse reinforcement replacing totally the use of conventional stirrups or as longitudinal core reinforcement apart from conventional rectangular stirrups, in improving the performance of RC beam in shear. The effect of WWMas a core zone reinforcement was quantified by introducing a parameter termed as 'Mesh Index'. Further the usefulness of 'mesh index' was studied in RC beams with different shearspan to depth ratio, provided with WWM as a core zone reinforcement. Also, the numericalsimulation of RC beams provided with welded wire mesh as shear reinforcement using ABAQUS is made and the results were compared with the experimental shear strength.

The investigation concluded that for the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM will be able to provide similar or better performance of RC beams compared to that of RC beams having conventional stirrups. Further the nature of failure / behavior of the RC beam remained more or less similar with the replacement of conventional stirrups with welded wire mesh as a core zone transverse reinforcement for the same spacing of transverse steel in the form of mesh / stirrups.

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INTRODUCTION

1.1 General

It is a known fact that the Reinforced Concrete (RC) due to its inherent advantages, occupies a prominent place among several materials used in building construction. While carrying the different building loads the reinforced concrete members are subjected to flexure, shear and torsional affects. While designing the structural elements, minimum desirable parameter considered is strength against flexure rather than remaining forces. Hence from the point of structural safety, the RC members are designed primarily to flexure and are normally engineered to fail in flexure rather than in shear at ultimate. This is because the shear failures are characterized by sudden and brittle in nature compared to the ductile modes of failure due to flexure. Shear failures, which in practicality are failures under combined shear forces and bending moments, are described by small deflections and lack of ductility. Several research studies conducted in the past have investigated about the factors affecting shear failure and developed numerous models, theories and designs to understand the same. The different types of reinforcement used for resisting shear in RC members include bent up / cranked bars, transverse reinforcement in the form of vertical or inclined stirrups. The bent-up bar capacity towards shear resistance in RC members is in general limited due to their in-effectiveness in the event of load reversals. Most of the design codes stipulate that the necessity for design of shear reinforcement in RC arises only when the effect of external shear exceeds the shear strength of concrete. Otherwise, the codes prescribe only certain minimum or nominal shear reinforcement. While there has been substantial advancement in comprehending and simulatingshear forces, it remains one of the most crucial aspects to address in reinforced concrete, even though it remains among the least understood. Most of the RC structural design codes of practice have followed a conservative approach for designing the members against shear failures.

1.2 Mechanism of shear resistance of concrete

For resisting different loads, the RC members are normally reinforced with both longitudinal and transverse reinforcement to take care of flexure and shear respectively. The resistance to shear in RC members is in general contributed by (i) Shear strength of concrete and (ii) Shear strength due to transverse reinforcement. The mechanism of shear capacity of concrete is in general composed of the contributions from the dowel action of the flexural reinforcement, Aggregate interlocking action or the crack friction, the shear stresses in uncracked concrete and the arch action. The magnitudes of these four mechanisms vary throughout the loading process and depend on cracking pattern and deformation of members. With the increase of applied shear load, the dowel action first reaches the ultimate then the aggregate interlock creates large shear. The failure of aggregate interlock necessitates a rapid transfer of shear to the concrete in the compression zone. The sudden transfer of shear to the concrete compression zone results in brittle failures. Except few cases where little warning is observed in shear failures and to be cautious in other cases of RC members. The prominence of the arch action is mostly related to the shear span to effective depth ratio, i.e, a/d ratio. The differences in the relative importance of these mechanisms have resulted in the development of shear strength theories of concrete. The assessment of shear strength of RC beams is very complex in nature and depends on several parameters which include depth of member, shear span to effective depth ratio (a/d), percent of flexural reinforcement, the cross-sectional area and spacing of transverse reinforcement and compression strength of concrete. The models based on flexure-shear interaction classifies the RC beams on the basis of shear span to depth ratio such as deep beams (a/d < 2.5) wherein the arch action is predominant and shallow beams (a/d >2.5) wherein the beam action is predominant (Slowik, 2014, Gunawan et al. 2020). ASCE-ACI Committee 445 indicated different types of RC beams based on a/d ratio viz: deepbeams (a/d<1.0), short beams (1 < a/d < 2.5) and ordinary shallow beams (a/d >2.5). The investigations made by Kani (Kani,1964) have indicated that the shear capacity decreases with the a/d increases.

1.3 Welded Wire Mesh (WWM)

Welded Wire Mesh (WWM), also known as welded wire fabric or wire mesh reinforcement, is aprefabricated steel wire mesh involving of parallel series of cold-drawn welded together insquare or rectangular grids. Each wire connection is joined by the electric arc welding. WWMis a versatile material commonly used in concrete structures for various applications. Itsincorporation provides numerous benefits to concrete elements, enhancing their performanceand longevity. Some of the primary applications of welded wire mesh in concrete structures: **Concrete Reinforcement**: Welded wire mesh is used as reinforcement in concrete to increase its tensile strength and resist cracking. By providing a network of interconnected steel wires, ithelps to distribute loads and stresses more effectively throughout the concrete, preventing thedevelopment of large cracks and enhancing the structural integrity of the element. **Slab andFloor Systems**: In slabs and floor systems, welded wire mesh is commonly placed at the mid-depth of the concrete to control shrinkage cracking and improve the load-bearing capacity. It helps in reducing the chances of cracks that can occur due to temperature and moisture variations. **Retaining Walls**: Welded wire mesh is used in the construction of retaining walls to reinforce the concrete and enhance its ability to withstand the lateral pressure of the soil or other retained materials. **Concrete Pavements**: In concrete pavements, such as roads, sidewalks, and driveways, welded wire mesh is used to enhance the durability and load-bearingcapacity of the surface. It helps to distribute the loads from vehicular traffic and prevent the formation of cracks. **Precast Concrete Elements**: In precast concrete elements like precast panels and beams, welded wire mesh is used to provide additional reinforcement and improve their overall strength and durability. **Shotcrete and Gunite Applications**: Welded wire mesh is often used in shotcrete and gunite applications, where concrete is sprayed onto a surface, to provide immediate reinforcement and enhance the bond between the concrete and the substrate.**Concrete Masonry Units**: In the construction of concrete masonry units like blocks and bricks,welded wire mesh is sometimes used to reinforce the units and improve their structural performance. **Tunnel Linings**: Welded wire mesh is utilized in the construction of tunnel linings to reinforce the concrete and provide stability to the structure. **Concrete Columns andBeams**: In cast-in-place concrete columns and beams, welded wire mesh can be added to improve their load-carrying capacity and prevent cracking. The representation of welded wire mesh is presented in fig.1.1

It's worth nothing that, the specific application and design of welded wire mesh in concrete structures may vary based on the project's requirements, load considerations, and engineering standards. Proper installation and integration with concrete are crucial to ensuring the desired performance and longevity of the structure.

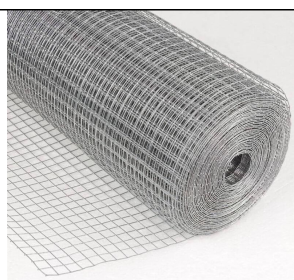
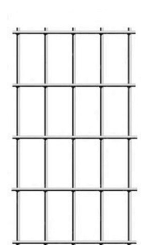
		
(a) WWM Bundle	(b) WWM- Rectangular aperture	(c) WWM – Square aperture

Fig 1.1 Welded Wire Mesh

1.3.1 IS Codes Related to Welded Wire Mesh

The following are some of the standard codes of practice on the use of WWM:

- IS 4948-2002: Welded Steel Wire fabric for general use —specification.
- IS l566 – 1982: Specification for Hard-drawn steel wire fabric for concrete reinforcement
- A1022/A1022M-16b—Standard Specification for Deformed and Plain Stainless-Steel Wire and Welded Wire for Concrete Reinforcement

- A1064/A1064M-18a—Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete
- WWR 500- Structural Welded Wire Reinforcement Manual of Standard Practice

1.4 ABAQUS software application

One of the influential finite element analysis software named ABAQUS which is widely used in engineering and research for simulating and analyzing various structural and mechanical systems, including reinforced concrete structures. ABAQUS can handle complex material behavior, large deformations, and non-linearities, making it suitable for simulating the performance of reinforced concrete under different loading conditions. Some of the key aspects of using ABAQUS for analyzing reinforced concrete:

Material Modeling: ABAQUS offers a range of material models suitable for simulating the behavior of concrete and reinforcing steel. For concrete, one can use models that consider compressive, tensile, and shear behavior, as wellas cracking and crushing. Reinforcing steel can be modeled with various material options, including plasticity-based models for steel bars.

Element Types: ABAQUS provides different element types suitable for modeling reinforced concrete structures, such as truss elements for modeling reinforcing bars, continuum elements for concrete regions, and interface elements formodeling the bond between concrete and reinforcement.

Non-linear Analysis: Reinforced concrete exhibits non-linear behavior due to cracking, crushing, and yielding of reinforcing bars. ABAQUS allows for non-linear analysis, enabling the simulation of the complete behaviorof concrete structures under different loading conditions.

In the present work the ABAQUS software is used in simulating the behavior of RC observed in the experiments.

1.5 Present research work

The analysis of RC beams using the principles of structural mechanics indicate a non-linear shear stress distribution across the depth of the cross section having maximum at the neutral axis i.e the core zone of the RC beams. The general practice of using stirrups placed periphery of the beam cross section and leaves the core zone of the section where high shear stress exists, unreinforced and thus makes the failure under shear as brittle. Further the practice of reinforcing the core zone of RC elements using fibers cannot eliminate completely the use of conventional stirrups / ties. Further in view of the soaring costs of labor and steel involved in bar bending work in making stirrups / ties, the prefabricated welded wire mesh would be an economically viable alternative. Several investigations in the past confirm that the RC elements such as slabs, wall panels reinforced with welded wire fabric showed better structural performance as compared to conventionally reinforced ones. In the present work an investigation on the novel means of using the prefabricated mesh (Welded Wire Mesh (WWM)) in central zone of beams used either in transverse direction replacing conventional stirrups / ties (or) as longitudinal direction with limited stirrups). The use of WWM will bring in simplicity and enable rapid fabrication of reinforcement cage required for RC members.

The main objective in the present investigation is to study the shear behavior of RC beams provided with welded wire mesh as shear reinforcement and compare and quantify the same with the shear performance of RC beams provided with regular stirrups.

1.6 Thesis organization

The following are the chapters classified to explain the thesis in a systematic way. This section gives an idea of different elements covered under this investigation.

Chapter 1: In this chapter the general aspects of shear capacity of Reinforced Concrete (RC) members and the general use of welded wire mesh were discussed. A brief on the present investigation with reference to the usage of WWM by way of shear reinforcement and the thesis organization were given.

Chapter 2: This chapter presents the literature review focusing mainly on the past investigations on the shear strength of RC members was presented. The gaps in the literature were identified that formed the basis for the present investigation.

Chapter 3: This chapter presents the research significance, scope and objectives of the investigation. The present investigation was planned in four phases to fulfill the objectives.

Chapter 4: In this chapter, phase-I work is presented that illustrate the efficacy of the core zone reinforcement in the form of welded wire mesh on the shear behavior of RC beams.

Chapter 5: This chapter presents the phase-II work in which the effect of welded wire mesh by way of transverse reinforcement replacing completely the conventional stirrups, on the shear strength of RC beams having shear span to depth ratio of 3, has been investigated.

Chapter 6: In this chapter, the effect of welded wire mesh by way of transverse reinforcement on the shear behavior of RC beams with varying shear span to depth ratio has been investigated and presented as phase-III work.

Chapter 7: This chapter presents the investigation as part of phase-IV that consisted of the study on the numerical simulation of the effect of welded wire mesh by way of transverse reinforcement in reinforced concrete beams using ABAQUS software.

Chapter 8: This chapter gives the conclusions arrived at after conducting the investigation on the use of WWM as shear reinforcement, in four phases.

Chapter 2

LITERATURE REVIEW

Chapter 2

LITERATURE REVIEW

2.1. Introduction

The extensive research and availability of literature on the flexural behavior of Reinforced Concrete(RC) have led to an understanding of the failure mechanism in flexure, and the related principles are well incorporated in different codes of practice. However, the performance and quantitative assessment of the behavior of RC in combined flexure and shear is still in active research. This chapter presents a review of the published research on different aspects related to the shear strength of reinforced concrete beams with and without shear reinforcement. The literature review is presented broadly in the following categories.

- Shear strength of reinforced concrete without shear reinforcement
- Shear strength of reinforced concrete with shear reinforcement
- Structural use of welded wire mesh – Application in flexure & shear
- Numerical simulation RC using ABAQUS
- Summary of literature review - Gaps identified

2.2. Shear strength of reinforced concrete without shear reinforcement

From the consideration of the equilibrium, the intensity of forces like shear or transverse throughout the cross-section of RC structural member can be represented by 'Shear force diagrams', and there will be a balance between the vertical and the horizontal shear stress intensities. When the shear stress equivalent to the principal stresses reaches the diagonal crack develops based on tensile strength of concrete. Several published experimental investigations have revealed different combined shear and flexure failure modes. The occurrence of these failure modes was related to the shear span to effective depth ratio (a/d). The various failure modes identified were: Diagonal tension failure / shear split tension failure ($2.5 < a/d < 6$), shear compression failure ($1 < a/d < 2.5$) and deep beam mode failure ($a/d < 1$). The shear transfer mechanism is typically influenced by the dowel action of the flexural reinforcement, Aggregate interlock and compressive strength of concrete. In the absence of web/shear reinforcement, the approximate contribution of these mechanisms to the total shear resistance of concrete will be: Dowel action (15 to 25%), aggregate interlock (35 to 50%) and compressive strength of concrete (20 to 40%).

Numerous empirical and numerical models have been proposed to calculate the shear resistance of concrete in RC beams without any shear reinforcement. The empirical equations resulting from experimental test outcomes were used in most of the codes of practice for estimating the shear strength of concrete. The shear resistance of concrete was influenced by different factors which is also included in code like i) Aggregate size ii) Longitudinal steel ratio, iii) Shear span to effective depth ratio and iv) Concrete compressive strength. The codes of practice such as IS 456, Euro code 2, BS 8110, and ACI 318 considered the effect of reinforcement ratio, effective depth and concrete compressive strength. In contrast, the Canadian code considers the shear strength a function of concrete compressive strength only. In Model code 2010, the shear strength of concrete in RC beams considers the parameter of web longitudinal strain and the aggregate size. The different codes of practice have used different expressions, as listed briefly in Table 2.1, for estimating the shear strength of concrete. An appraisal of these shear strength expressions has indicated different shear strengths of concrete for similar percentages of longitudinal reinforcements and gives scope for further research, particularly in the context of increased use of new concretes.

Table 2.1 Shear strength of concrete

Code of practice	Expression for shear strength of concrete	Remarks
European Code	$V_c = \left[\frac{0.18}{\gamma_c}\left[100\rho_1 f_{ck}\right]^{1/3}\left[1+\sqrt{\frac{200}{d}}\right]\right]b_w d$ $\rho_1 = \frac{A_{s1}}{b_w d} \leq 0.02$ and $k = \sqrt{1+\frac{200}{d}} \leq 2$	Where A_{s1} is the Area of the tensile reinforcement, which extends $\geq$ (l_{bd} +d) beyond the section considered, b_w is the smallest width of the cross-section in the tensile Area in mm, where f_{ck} is the cylinder compressive strength of concrete in MPa. γ_c is the concrete partial factor of safety taken as 1.5. It considers the concrete compressive strength, reinforcement ratio and span-to-depth ratio.
British Code	$V_c = \frac{0.79}{\gamma_m}\left[\frac{100A_s}{bd}\right]^{1/3}\left[\frac{400}{d}\right]^{1/4}$	$100A_s/bd$ is the reinforcement ratio, ranging from 0.15 >$100A_s/bd$ < 3. 400/d reflects the size effect and should not be less than 1 for members without web reinforcement. γ_m is the concrete partial factor, taken as 1.25. For concrete compressive strength (f_{cu}) greater than 25N/mm^2, the above

Table 2.1 Shear strength of concrete		
Code of Practice	**Expression for Shear strength of concrete**	**Remarks**
		equation is multiplied by $(f_{cu}/25)^{1/3}$ to account for the influence of higher compressive strength on the shear strength. The value of fcu should not be greater than 40
American Code	$V_c = \left[\frac{\lambda\sqrt{f_c^{'}}}{6}\right] b_w d$ $V_c = (0.16\sqrt{f_c^1} + 17\rho_w \frac{V_u}{M_u}) b_w d$	Where f_c^1, ρ_w, b_w,d are the concrete compressive strength, flexural reinforcement ratio, width and effective depth of the beam, respectively. λ is a factor that accounts for lightweight concrete. For normal concrete, λ is taken as 1. Vu and Mu are factored shear force and bending moment occurring simultaneously in the critical section considered
Canadian code	$V_c = 0.2\sqrt{f_c^{'}} b_w d$	where f'_c, d and b_w are the concrete compressive strength in MPa, effective depth and width of the beam, respectively.
FIB Model code	$V_c = k_v \frac{\sqrt{f_{ck}}}{\gamma_c} z b_w$ Level-I approximation: $K_v = \frac{180}{1000 + 1.25z}$ Level-2 approximation: $K_v = \frac{0.4}{1 + 1500\varepsilon_x} \cdot \frac{1300}{1000 + k_{dg} z}$	Where fck is the characteristic compressive strength of concrete in MPa, b is the width of the section in mm, and z is the effective shear span depth and is assumed to be 0.95d in reinforced concrete members. γ c is the concrete partial factor of safety. The term kv considers the influence of strain on the web and the aggregate size. Model code 2010 offers two levels of approximation to determine kv in beams without shear reinforcement.
Indian code	$\tau_c = \frac{0.85}{6\beta}\sqrt{0.8 f_{ck}}(\sqrt{1+5\beta} - 1)$ $\beta = \frac{0.8 f_{ck}}{6.89 p_t} > 1$ $p_t = \frac{100 A_s}{b_w d}$	Where, *fck* = compressive strength of concrete at 28 days in Mpa, $b_w d$ = width and depth of effective cross-section in mm, Pt = longitudinal reinforcement ratio, As = Area of steel bar in mm^2.

The analysis of the relation between the rate of change of bending moment and the shear force throughout the span gives rise to two different modes of shear resistance: (i) Beam action and (ii) Arch action.

V = dM/dx = d/dx (T jd) = jd (dT/dx) + T (d(jd) /dx), where T= Tensile force in the longitudinal reinforcement and jd is the lever arm.

The first term, i.e., jd (dT/dx), represents the behavior of a prismatic flexural member wherein the tensile force changes in tune with the bending moment leading to the 'Beam action' in the shear resistance. The prerequisite for this action to be predominant is the relation between concrete and steel. In the beam action, there will be a formation of the number of free concrete teeth cantilevers. The beam action in shear resistance will be significant for a/d > 2.5.

The second term, i.e., T (d(jd) /dx), becomes prominent when the bond among steel and concrete is damaged due to the formation of splitting cracks along the reinforcement. Under this circumstance, the transfer of external shear depends on the inclined internal compression in concrete. The proper anchorage of flexural reinforcement becomes reason for developmentof arch action near the supports. The arch action in shear resistance will be significant for a/d <2.5.

Kani, (1964): Attempted to explain and answer two points regarding the characteristics of Reinforced Concrete(RC) beams (a) The shear failure internal mechanism in RC beams and (b)The reason for the strength of the developed mechanism. With the application of load, the reinforced concrete beam is considered as comb-like structure. Due to load application at the top, the concrete beam divides into a tensile zone at the bottom and a compression zone at the top of the beam. The tensile zone developed with flexural cracks is considered concrete comb teeth. Similarly, the compression zone is taken as the backbone of the concrete comb. It is stated that the analysis of the reinforced beam involves two mechanisms: The beam-like behavior arises when the concrete teeth capacity is not exceeded, and arch behavior occurs when the capacity gets exceeded. The results indicated that the capacity of concrete teeth is lower forless shear span-to-depth ratios(a/d). It is also stated that with the increase of load application gradually, the beam behavior gets changed into an arch-like behavior and exceeds the concrete teeth, resulting in failure.

Rebeiz et al. (2001): Studied the ultimate shear strength and cracking shear strengths of RC beams without shear reinforcement considering the effects of variables of beams like compressive strength (fc), tensile reinforcement ratio (r), and shear span-to-depth ratio (a/d). It is stated that the shear span-to-depth ratio is an important factor; as it increases, the ultimate shear strength decreases. The compressive strength of the concrete also has a significant role, but a minimal effect is observed with the variation of the tensile reinforcement ratio.

Subramanian (2003): Studied the shear strength equations of different codes and extended study for high grade concrete beams and compared among different codes. It is observed that Normal Strength Concrete(NSC) beams available are not applicable to extrapolate to High Strength Concrete(HSC) beams. The IS code equations show very conservative results. American, British and Norwegian codes are proven to be safe designs as these results are conservative. Australian and New Zealand code results show unsafe HSC beams for the provision of shear. CEB-FIP model agrees with the numerical results and is in good agreement. Hence it is suggested to adopt this formula for HSC beams of Indian code with required modifications.

Cladera & Mari (2004): Studied the behavior of RC beams without web reinforcement of high and normal strength beams considered. A rational method is developed to assess the shear strength using an artificial neural network of normal strength and high-strength reinforced beams. A general shear design is developed using the ANN technique, considering the size effect and concrete compressive strength.

Hong & Ha (2012): Studied the impact of diagonal cracking and its mechanism on beams' shear strength without reinforced concrete beams' web reinforcement. The width of the concretestrut gets reduces due to diagonal cracking reducing its strength. A model is proposed to studythe shear cracking and ultimate strength. It states that inclined cracking is propagated based onthe combination of tension and stress due to bond between concrete and steel. The diagonal crack propagates into the member, concrete strut gets reduces its width and strength. From thestress trajectory, the degree of penetration is identified with the point of intersection of the yieldline of the strut and the diagonal crack. The parameters considered are concrete compressive strength and shear span-to-depth ratio.

Arslan & Polat (2013): Studied the shear strength of RC beams due to contribution of concrete is investigated. The study was performed under monotonically increased cyclic loading and investigated the contribution of concrete. It is stated that the concrete and shear contribution for enhancing the shear strength is similar to the first shear crack up to its beam mid-height. The shear strength degradation is also observed for the given loading estimating, and it may be due to the yielding of transverse reinforcement resulting in the unclose of cracks. It is also stated that for reversed cyclic loading, 18-69% contribution of concrete is observed for enhancing the shear strength.

Somraj, (2013): Studied the shear failure of reinforced concrete beams under dynamic conditions with the application of rapid loading and used a strut-and-tie model for analysis. The primary parameters considered are varying loading rate and shear reinforcement ratio for the shear span-to-depth ratio of 1.9 and 3.3. For the shear span-to-depth ratio of 1.9, the failure mode is shifted from brittle to ductile and fails in shear compression with the increasing of transverse reinforcement ratio. Beams failed in diagonal tension for the shear span-to-effective depth ratio of 3.3. The influence of loading rate is more when less shear span-to-effective depth ratio and transverse reinforcement ratio are used.

Gandomi et al. (2014): Proposed a model and expressions for prediction of shear strength of RC beams without stirrups using linear genetic programming methodology. Parameters formulated in this model are (a/d) ratio, size of aggregate, concrete cylinder strength, lever arm, and percentage of longitudinal reinforcement. This linear genetic programming model proves the best results compared to other building codes.

Carmona & Ruiz (2014): studied the effect of a bond between the reinforcing bars and the size effect on the shear strength of reinforced concrete beams without web reinforcement. As bond strength increases, shear failure formation reduces as the steel bars yield before the crackextends to the critical depth. This critical depth where shear failure occurs, or section collapses.The size effect is taken from the bazant's Law.

Słowik, (2014): Investigated the longitudinally RC beams shear capacity and its failure mechanism without web reinforcement. It is observed that beam size, shear span to effective depth(a/d) ratio and effective length to depth ratio affect the beam failure mechanism. It is stated that, with the increase of beam depth, the ultimate shear capacity reduces. It is detected that different failure patterns are observed with different effective length-to-depth ratios for the same (a/d) ratio.

Jeong & Kim (2014): Proposed a model to explain the discrete contributions of the shear strength of RC members. In this model, beam and arch action are two prominent shear-resistant mechanisms involving the relation between shear and bending moment($V=dM/dx$). The compatibility conditions have arrived coupling with two actions, and basic truss ideology is considered. The fundamental relation is again modified as ($V=dM/dx= z\, dT/dx + T\, dz/ dx$), where these two components reflect both arch and beam actions.

Shuraim, (2014): Presented a new procedure for determining shear capacity by coupling the shear resistance and shear demand of reinforced concrete members. The shear capacity is determined using the relation of longitudinal bending strain and concrete tensile strength. Enhancing parameter is accommodated to the relation for the effect of arch action having a shear span ratio less than 2.5. Shear demand and resistance curves are also developed to determine the fundamental shear strength considering their intersection point.

Li & Leung (2016): Studied the shear span-to-effective depth(a/d) ratio influence on the behavior of reinforced concrete beams strengthened with FRP strips as shear reinforcement. This study was conducted for the a/d ratio of 1.0 to 3.5. The results indicated that FRP strips as shear reinforcement proved that shear capacity increases with the increase of a/d ratio up to the limit of a/d ratio=2.5 later, it decreased. The results are also compared with different codal shear provisions. It is stated that FRP strips as shear reinforcement are the preferable reinforcement for medium a/d ratio then, followed by large a/d ratio and not much preferable for small a/d ratios.

Alyousif et al. (2016): Investigated the shear behavior of reinforced concrete beams with three different shear span to depth(a/d) ratios of 1,2,3, and another parameter considered is the percentage variation of longitudinal reinforcement. The beams are tested and categorized into two different groups; one group is with engineered cementitious composites (ECC), and another group is with conventional concrete. Various parameters like load carrying capacity, stiffness, ductility, and energy absorption capacity variations with respect to the (a/d) ratio are analyzed. The results show that load carrying capacity, yield stiffness, ductility and energy absorption capacity get reduced with an increase of (a/d) ratio. The increase in the percentage of longitudinal reinforcement also increases energy absorption capacity.

Kim et al. (2018): Proposed a rational shear strength equation to predict using different contributions of components like aggregate interlock, dowel action of the longitudinal bar and concrete compressive strength without transverse reinforcement. This equation interlinks the bond action of longitudinal reinforcement to each component. It is experimentally verified with four different shear span to depth ratios as 2,2.5,3 and 4. It was observed that shear resistance due to concrete is 47%-57% of the whole shear force developed. Dowel action of flexural reinforcement is 25%-30% of the entire shear force and increases with the increase of shear span to depth ratio. The shear contribution due to aggregate interlock is 18-30% of total shear resistance, decreasing with the increase of shear span to depth ratio.

Demir et al. (2019): Studied the diagonal cracking and crack width of reinforced concrete deep beams with the parameters of shear span to depth ratio, concrete compressive strength and height of the section. When section height increases, load carrying capacity increases and a slight increase in crack width. The increase of the a/d ratio results in decreased shear strength of RC beams and increased crack width. The increase in compressive strength impacts shear strength much but reduces diagonal crack widths.

Gunawan et al. (2020): Proposed a new calculation method to estimate the shear capacity of RC beams considering two mechanisms as beam and arch action using different equations. In this method, parameters like varying stirrup ratio and shear length ratio are used and analyzed for these mechanisms testing under two-point loading. It is stated that, with the increase of stirrup ratio, beam action decreases, and arch action predominates but for smaller shear spans.

2.3. Shear strength of reinforced concrete with shear reinforcement

The shear strength of the RC beam can be substantially increased by the provision of shear reinforcement, also called web reinforcement / Transverse reinforcement. The most common type of web reinforcement (shown in Fig 2.1) used is Vertical or inclined stirrups. Recently the use of 'Swimmer bars' were proposed as web reinforcement. Sometimes the web reinforcement is used in combination with the Bent-up bars.

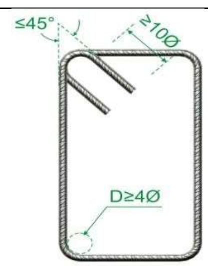
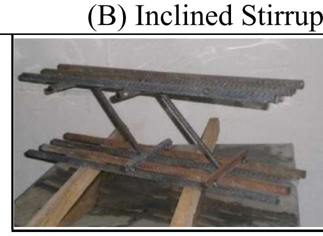
	
(A) Vertical stirrups	(B) Inclined Stirrups
	
(C) Bent-up bars	(D)_ Swimmer bars

Fig. 2.1 Types of Shear reinforcement

Including web reinforcement does not fundamentally change the mechanism of shear resistance. However, the total shear strength gets enhanced significantly due to the web reinforcement's interception of the shear cracks. The presence of web reinforcement is advantageous in strengthening the beam action in a number of ways, such as: improving the contribution of the dowel action, suppressing the flexural tensile stresses, limiting the widening of shear cracks, providing confinement etc.

The different approaches in estimating the shear strength of RC members in the presence of transverse reinforcement include (i) Truss models, (ii) Modified Compression Field Theory(MCFT) and (iii) Strut and tie models.

2.3.1. Truss models

The Truss models for shear in RC exhibit an exceptional concept model for representing the forces in a cracked concrete beam. In truss models, it was postulated that after the RC member cracks due to shear tension, the beam could be considered a parallel chord truss with compression diagonals or simply concrete struts which are inclined at 45 degrees with respect to the longitudinal axis of the beam. Truss models neglect the tensile strength of concrete. The effect of diagonal compression pushes away the upper and bottommost faces of the beam, whereas the stresses due to tensile forces in stirrups retain them together while maintaining equilibrium. The shear capacity is assumed to be reached when the stirrups reach the yield stress. Most of the shear design codal provisions were based on these truss models.

2.3.2. Modified compression field theory

The Modified Compression Field Theory (MCFT) is a general model of the load-deformation behavior of an RC beam subjected to shear. This model uses the equilibrium, strain compatibility and stress-strain relationship while determining the angle of inclination for the inclined tensile stresses. The main assumption in this theory is the coincidence of principal strain directions with that of principal stress directions. The main difference between the truss model and MCFT is the concrete contribution towards shear strength. In the truss model, the concrete influence does not vary with the quantity of transverse steel, whereas in MCFT, the concrete influence depends on crack width. i.e., the huge transverse reinforcement, the lesser the crack width and the greater will be the concrete contribution. A few codes have adopted the MCFT theory as the basis of design for shear (Canada, Norway and in the AASHTO LRFD).

2.3.3. Strut and Tie models

The Strut-and–tie model (STM) is one of the truss models wherein the forces developed in the distributed or discontinuity or D-regions in a beam are evaluated in the shear design. The regions other than distributed are called bernoulli's, or beam regions indicated as B-Regions. The identification of B and D-regions, especially for deep beams, is indicated in this model. In deep beams, the distribution of flexural stress is nonlinear, so the conventional flexural theory is not applicable. Because of the effects of localized conditions developed by applied load, resulting in dissipating the force which is away from the load resulting from developing the D-regions. Truss distribution is observed based on the developed crack patterns, which cracks need to be assumed with the experience. This model is a combination of struts for compressionand ties for tension connected at nodes in a truss is considered, and this model is derived usinglower bound theorem of plastic theory. The top compression strut is due to concrete, and the bottom tension tie acts due to longitudinal reinforcement. The shear forces use to transfer top and bottom through an inclined compression chord due to concrete, whereas stirrups act as vertical ties. A model explains that the occurrence of a crack resulting in the width of the diagonal strut seems to be reduced and also results in a less shear capacity of the member (Hong& Ha, 2012).

Mansour et al. (2004): Estimated the ultimate shear strengths of reinforced concrete beams using transverse reinforcements using Artificial Neural Networks (ANNs) application. ANN nineinput data cover the cylinder compressive strength, yield strength of reinforcing bars, the shear-span-to-effective depth ratio, the beam's cross-sectional dimensions, and the flexural and web reinforcement ratios. Results indicated that with the increased concrete strength, the (a)shear span-to-effective depth ratio decreases, and (b) the quantity of flexural and web reinforcement increases.

Cladera & Mari (2004): Studied the shear capacity of RC beams of normal and high-strength beams with shear reinforcement. An Artificial Neural Network(ANN) technique is used to assess the shear capacity by considering the shear procedures of different codes. The beam strength of concrete depends on the quantity of web reinforcement and the beam size. Concrete compressive strength is directly proportional to failure shear strength. Generally, the shear design considers the relation among the bending moment and shear for the given section. A basic shear design method is developed without considering the bending moment and produces conservative results.

Cladera & Mari (2005): Studied the shear performance of high grade strength reinforced concrete beams with and without web reinforcement. A minimum amount of web reinforcement is proposed relating to concrete tensile strength. Parameters considered in the investigation are web and flexural reinforcement.

Esfahani et al. (2009): Attempted to explain the cracking behavior due to the shear of RC beams. Various parameters were considered in the investigation, such as lateral concrete cover to stirrup, spacing of web reinforcement, stirrup configuration, flexural reinforcement ratio, loading paths and shear crack width. It is observed that shear crack widths depend on shear reinforcement strain and opening of diagonal crack, and this crack spacing is higher in larger beams than smaller beams. The greater shear crack width is identified with the increase of side concrete cover and spacing's of stirrups. A shear crack opening is better controlled with the increased longitudinal reinforcement as it creates smaller cracks. Shear crack width does not differ much with loading paths.

Kuo et al. (2010): Studied the shear performance of reinforced concrete beams by developing an analytical model. This model focused on determining transfer mechanism of forces considering the load paths of Beam(B) and Disturbed(D) regions. The variables that affect these regions are beam geometry, flexural bars and shear reinforcements. This study classifies the beams into three categories: short beams(DD), slender beams(DBD) and deep beams, as this method clearly defines the lengths of the 'D' region; apart from ACI code classification, a new segregation of beam named as short beam is proposed. Because of abolition of B regions overlap of D regions in the short beam expected to be shear tension failure resulting in uncontrolled crack propagation. The shear crack inclination of angle is too estimated based on force transfer and its load paths.

Gedik et al. (2011): Studied the performance of a new lateral stirrup, especially in short deep beams, as it is observed that the contribution of vertical stirrups is almost negligible in the case of a/d=0.5. This lateral stirrup performed better in the form of ductility and load-carrying capacity and also played a significant effect on parameters like lateral deformations and concrete spalling. High energy dissipation and load-carrying capacity are observed.

Varney et al. (2011): Studied the shear capacity of reinforced concrete beams with the impact of improperly anchored stirrups. These stirrups are fabricated with standard hooks and tested until failure load. It is stated that improperly anchored stirrups have little impact on RC sections' shear strength.

Al-Nasra & Asha (2013): proposed a new type of shear reinforcement as swimmer bars which are oblique bars welded to upper and bottom reinforcement longitudinal bars. Beams with swimmer bars are advantageous in improving stiffness, load carrying capacity by nearly 25% over conventional stirrups. The number of shear cracks that appeared is less, and crack width and deflection are also less than traditional beams.

Liu & Mihaylov (2016): Studied the different models of deep beams and presented their summary. Some models include strut-and-tie models, two-parameter kinematic theory (2PKT), upper-bound plasticity models, shear panel models, other mechanical models and artificial intelligence models. Strut-and-tie model and two-parameter kinematic theory (2PKT) are the most reliable methods for deep beams. These methods are much focused and studied various variables of a/d, shear reinforcement ratio, tension reinforcement ratio and effective depth. It is observed that 2PKT shows uniform results with test variables, but the strut-and-tie model gives less computational effort.

Shatarat et al. (2016): Studied the new continuous spiral rectangular transverse reinforcement effect in reinforced concrete beams and tested under four-point bending. The variables like shear span to depth ratio, spacing's and inclination angles of stirrups are adopted. The proposed beams' crack configurations and failure modes are the same as regular stirrups. Improvement of shear capacity and ductility is observed compared to regular stirrups with the advantage of reduced cost.

Mohamed, (2017): Investigated a new type of transverse reinforcement as swimmer bars which are oblique bars welded to upper and bottom reinforcement longitudinal bars. Two types of swimmer bars, that is, swimmer bars with two and three planes, are considered in this study. Compared with traditional stirrups and tested varying compressive strength. This shear reinforcement improves ultimate shear stress, cracking stress, and shear strain. Also observed the better failure modes with reduced deflections with slow crack propagation. Based on several swimmer bar planes, the failure mode shifted from shear to flexure and performed better than conventional stirrups.

Hu & Wu (2017): Studied the brittle failure of shear cracking behavior of reinforced concrete beams. The position of diagonal cracking is identified from the direction of principal shear strains during loading. Identification of position is taken from the contour lines of strains. The strains due to transverse reinforcement(Vs) are calculated using strain gauges, and the shear strength of the contribution of concrete (Vc) is taken experimentally. The average shear and principal strains are obtained using digital image correlation(DIC). The analysis states that before the crack formation, the principal shear strain increases with the increase of shear force until the initial inclined crack. Later it reduces with the increase of shear force.

Wu & Hu (2017): Studied the components of shear resistance of reinforced concrete beams as shear resistance due to web reinforcement(Vs) and shear resistance due to concrete (Vc). Vs is achieved using the strain gauges attached to the transverse reinforcement. The variation of Vc and Vs fluctuates throughout the loading process. Both Vc and Vs increase with the increase of deformation. Until the first diagonal crack is formed, the shear resistance is taken by the contribution of concrete Vc. Later, Vs contribution comes into consideration, it increases, and Vc gets slows, but it continues till it reaches the peak value. Further, Vc decreases and gets neutral until the final failure, but the remaining resistance is provided by transverse reinforcement.

Baghi & Barros (2018): Studied the Simplified Modified Compression Field Theory (SMCFT) and assessed the shear strength of reinforced concrete beams using a design-oriented approach. Based on this concept, new equations are developed to determine parameters like cracked concrete tensile stress factor (β) and diagonal compressive stress inclination (θ). Coupling these equations with SMCFT equations obtained the shear strength of RC beams avoiding the iterative process.

Hu & Wu (2018): Investigated the shear behavior constituents of reinforced concrete beams with different shear span-to-effective depth ratios. The shear components are shear resistance due to concrete (Vc) and shear resistance due to stirrups (Vs), which are measured along with the shear resistance of first diagonal cracking (Vcr). The test results were also compared with a few models and codes. It is stated that Vc gets reduced with the increase of the a/d ratio, whereas Vs increases with the increase of the a/d ratio. Vcr did not show any clear trend variation concerning the a/d ratio, so it is not considered a shear contribution component. But Vcr is observed as greater than Vc when the a/d ratio is large and much smaller than Vc when the a/d ratio is less. Most models and codes overestimate the Vs, and Vc is considered conservative when the a/d ratio is less than 2.5. When the a/d ratio is greater than 2.5, Vc is overestimated, and Vs is shown to be conservative.

Zhao et al. (2018): Studied the rust characteristics provided with different shear reinforcements arrangements like regular stirrups and insulated stirrups and without stirrup is studied. Among these three arrangements, a traditional stirrup has faster corrosion crack propagation than the remaining cases and damages the concrete cover. So the arrangement of shear reinforcement greatly influences corrosion characteristics and concrete cover.

Ghahremannejad & Abolmaaji (2018): Developed a new methodology for conducting displacement control analysis to determine the shear capacity of reinforced concrete beams under distributed loads. To apply single displacement on the framework due to distributed loads is set up by the new framework consisting of sub-frames. Using this arrangement, the uniformly distributed load is applied and compared with the application of a concentrated load of RC beams for four shear span-to-effective depth ratios of 3,4,5 and 7. It is observed that the shear strength of RC beams due to uniformly distributed loads is 76% more than the shear strength of RC beams with concentrated loads.

Chen et al. (2018): Proposed a Cracking Strut-and-Tie (CSTM) Model to determine the shear strength of reinforced concrete deep beams based on the Strut-and-Tie(STM) Model. The CSTM model divides the concrete strut into cracked and uncracked parts. The proposed method applies to practical designs and reinforced beam deep beams with and without shear reinforcement. This method, with parameters like shear span-to-effective depth ratio, web and flexural reinforcement ratio, effective depth and concrete compressive strength, is better than a strut-and-tie model for predicting the shear resistance of RC deep beams.

Zhang et al. (2020): Studied the shear performance of high grade strength concrete deep beams with various parameters. Parameters considered in the study are small shear span to depth ratios of 0.3,0.6 and 0.9 and the percentage of longitudinal tensile reinforcement ratios of 0.67%, 1.05%, 1.27% and also vertical stirrup ratios of 0%, 0.25%, 0.33%, 0.5%. The output parameters considered are load-carrying capacity, deflection characteristics, strains of steel bar and concrete and failure modes. The experimental results indicated that an increase in percentage of longitudinal reinforcement and a decrease in shear span to effective depth ratio increases the shear capacity of beams. The deep beams with small shear span to depth ratio beams used to fail with diagonal compression. The increase in vertical stirrup ratios has the advantage of controlling crack characteristics like propagation and opening and also improving its ductile behavior up to a certain limit. Further increase of vertical shear reinforcement does not enhance the shear capacity and may result in compression failure of concrete. The obtained shear capacity results are compared with the codes, which rely on the strut-and-tie model.

Hunegnaw & Aure (2021): Studied the shear behavior of reinforced concrete beams for the effect of stirrup orientation considering the parameters varying as shear span-to-depth ratio and concrete strength. Test results showed that the shear capacity of inclined shear reinforcement is more than vertical shear reinforcement. Shear capacity also improved for shear-to-depth of 2.2 than 2.6. With the increase of compressive strength of concrete then shear capacityincreases. The above study results are compared with different codal shear provisions resultingin these codes showing conservative results, which increase with the reduction of the (a/d) ratio.

Yoo, (2022): Evaluated the performance of new shear reinforcement formed by integrating steel plates and N-type bent rebar and assessed its enhanced shear capacity. Compared with the individual performance of each shear reinforcement and tested under four-point loading. The web reinforcements of both types show an improvement of 60% shear capacity. N-type rebar did not exceed the nominal strength as it does not yield sufficiently, whereas steel plate reinforcement yielded sufficiently.

Zhou & Wan (2022): Proposed a new Modified Strut-and-Tie Model (MSTM) for determining the shear performance of Ultra-High-Performance Concrete(UHPC) beams. In this model, the truss and arch action is decoupled based on the principle of complementary energy with some simplified models**.** The above model tested for small shear span to depth ratio predicted the shear results and validated with some codal shear provisions**.** It is stated that when a shear span-to-depth ratio of $\lambda \leq 0.75$, the arch behavior dominates and its shear capacity is governed by inclined struts. When the shear span to effective depth ratio $\lambda \geq 3.0$, the beam action dominates and shear capacity is taken from the truss model. For $0.75 < \lambda < 3.0$, this model predicts the behavior of UHPC beams where the arch action quickly decreases into another form.

2.4. Structural use of welded wire mesh – Application in flexure and shear

Welded Wire Mesh (WWM) is a sequence of corresponding longitudinal wires welded to transverse wires by electric fusion method with required spacing. The process of welding is performed by machinery, so that accurate dimensions which results in economical and also saves time and labor. It is observed that the welded wire mesh structural performance is similarto mild steel bars or HYSD bars. This high strength is expected to be due to characteristic strength of welding phenomena. Specially in the case of WWM, the outer surface area is the responsible factor for the concrete bond. The proper mechanical connections with welding to the transverse wires are responsible for transfer mechanism of stress from steel to concrete andconcrete to steel. The strong mechanical welding at each point and finer spacing of welding wire are two main factors responsible for reduction of cracks in the concrete. The close spacingof wires is effective phenomena for non-load phenomena and stresses due to shrinkage and temperature changes. The structural integrity of welded wire fiber is retained due to above phenomena. Adequate savings of time and labor is the huge advantage in welded wire fabric.It is observed that no much laborious process involves like cutting, marking and spacing whiledeveloping of binding wires.

The major advantage is flexibility of handling because of the utility of thinner wires. Due to availability of long length rolls, welded wire mesh helps to usage of all repair works by re-plastering.

Xuan, (1987): Investigated the influence of Welded Wire Fabric(WWF) as transverse reinforcement in reinforced concrete T-beams. Mostly beams are provided with outer-surface welded wire fabric as web reinforcement and different stirrups patterns were developed and tested. On regular conventional beams and one beam without stirrups these were also developed and tested under static loading conditions and compared with conventional beams. The results indicated that welded wire fabric as shear reinforcement performed well in anchorage and ductility and observed slight distribution of diagonal cracks.

Ayyub et al. (1994): Investigated the bond strength of Welded Wire Fabric(WWF) up to their ultimate capacity by conducting pull-out tests in concrete bridge decks. The pull-out results indicate that even with the failure of the bond between the longitudinal wires and concrete, additional loads are carried due to the anchorage effect of transverse wires and weld shear strength; this effect is observed even after the first slippage. But the contribution of longitudinal wires is observed to be very less, stating the reason may be due to confining effect of surrounding concrete and transverse wires. Finally, it is noted that a 16 to 771% increase in bond strength is observed with different arrangements of longitudinal and transverse wires.

Ayyub et al. (1994): Investigated the tensile strength and ductility of different manufacturing Welded Wire Fabric(WWF) that it is aiming to be suggested to use as structural reinforcement. The steel wires included cold-drawn wires, plain and deformed wires, tempered and non-tempered wires and epoxy-coated wires. The results indicate that cold-drawn wires showed increased tensile strength with reduced ductility. Tempered and epoxy-coated wires show slightly higher ductility and reduced tensile strength. It is stated that WWF shows enough ductility required for structural use.

Ayyub et al. (1994): Studied the concrete bridge deck slabs reinforced with Welded Wire Fabric(WWF) as splicing strength by testing slabs with and without a splice. It is perceived that the arrangement of cross wires and longitudinal wires and their distribution plays a prominent role in improving the splicing strength of slabs. The slabs without transverse wires welded to longitudinal wires show similar results to slabs without a splice.

Bischoff et al. (2003): Studied the behavior of slabs provided with welded wire reinforcement along with different types and dosages of fibers subjected to concentrated load. Slabs with fibers are effective in improving the load-carrying capacity compared to welded wire reinforcement, but its difficult slabs construction on the ground and intend to crack control.

Tabsh, (2007): Studied the strength and ductility of high-strength concrete columns provided with Welded Wire Fabric(WWF) provided laterally. The performance of high strength concrete columns subjected to axial compression with WWF is compared with unconfined columns. Substantial improvement of strength and ductility is observed compared to unconfined columns taken from the stress-strain curve of concrete.

Amorn et al. (2007): Investigated the fatigue behavior of deformed Welded wire reinforcement(WWR) having high strength. WWR's are manufactured under controlled conditions, so they have high yield strength. A conservative stress equation is developed from the obtained results, and WWF performed better under fatigue loads because of its cross wires.

Ghiassi & soltani (2010): Developed a rational equation to predict the shear strength of reinforced concrete members. In this, a computational model developed by predicting RC members' post-cracking behavior on account of local stress between the cracks and microscopic stress across the cracks is considered. These models and equations can be used for RC members with welded wire mesh, different bar distributions and consideration of size effect.

Hadi & Zhao (2011): Investigated the effectiveness of cheaply available materials, such as fly screen meshes and steel wire meshes, to reduce the high-strength concrete column cover spalling. An experimental investigation is conducted on cylinders with different fly-screen and steel wire meshes. The results indicate that the steel wire meshes performed better in enhancing the load-carrying capacity, and fly screen meshes performed better in improving the ductility of the specimens. This phenomenon is observed for different loadings like central and eccentric loads and pure bending. These materials prove the economical solution to improve the ductility and load-carrying capacity of the columns.

Ibrahim, (2011): Studied cementitious slabs simply supported on four edges and subjected to patch load using wire mesh with varying volume fractions. The test variables were the wire mesh volume fraction: expanded diamond and square types; The test results showed that as the volume fraction increased, the ultimate strength of the slabs increased and reduced deflection. Ductility and stiffness properties are also improved.

Alexander & Ramakrishnan (2016): Studied the flexural behavior of RC beams provided with welded wire mesh. The welded wire mesh is from prefabricated cold-drawn wires arrangedin two orthogonal directions. It yields the maximum load-carrying capacity with numerous advantages like quality control and economical.

Mansuri et al. (2017): Studied reinforced beams with welded and weaved mesh to strengthen the beam and micro-concrete. The ultimate load-carrying capacity is increased with welded mesh and reduced deflection. The reduced deflection is observed for both at first crack and ultimate loads.

Shaaban, (2018): Studied the flexural behaviour of lightweight ferrocement composite beams were reinforced with either Expanded Metal Mesh (EMM), Welded Wire Mesh (WWM) or Fibre Glass Mesh (FGM). Beams reinforced with WWM reflect better ductility and show fewer cracks with greater crack widths than conventional reinforcement.

Gayathri & Kirthiga (2018): Studied the flexural and shear behavior of reinforced concrete beams such that welded wire mesh provided by way of shear reinforcement was tested in two-point loading and different parameters were assessed. The flexural strength of beams is increased compared to conventional beams provided with welded wire mesh by way of shear reinforcement. A similar crack pattern and failure mode is observed with beams of welded wire mesh and conventional ones. If the mesh is entirely distributed throughout the length, the beam performs better than other beams, and it again depends on the volume per cent of the mesh provided. More volumetric mesh beams yield better results, but it is the best alternative to conventional stirrups with reduced cost.

El-Sayed & Erfan (2018): Studied the shear performance of Ferro cement concrete specimens using steel reinforcement, expanded and welded wire mesh. The wire mesh is provided concerning the weight of the stirrups. Beams with welded wire mesh show improved shear capacity compared to expanded wire mesh, showing the multiple features of the steel reinforcement. Because of the lightweight, easier to cut, handle and bend and flexible for complex and curvature structures, welded wire mesh has better features than steel reinforcement. Ferro cement concrete with welded wire mesh exhibits better load-carrying capacity, deflections, and stiffness over other reinforcements, and this was further improved by increasing the layers.

Albidah et al. (2019): Investigated the reinforced concrete beams with welded wire mesh, such as near-surface shear strengthening experimentally and compared them with conventional steel transverse reinforcement. All beams are provided such that half of the beam is provided with regular web reinforcement, and the remaining half is provided with strengthening material. Based on the modified strut-and-tie model, a methodology is developed to assess the shear strength. Based on this methodology, the beams with welded wire mesh proved to have a higher shear capacity than those with conventional stirrups.

Cui et al. (2019): Studied the Welded Reinforcement Grids(WRG) as shear reinforcement in reinforced concrete beams subjected to monotonic and cyclic loading and compared them with conventional non-deformed and deformed stirrups. The behavior of WRG beams, along with their failure modes, is the same as beams with undeformed stirrups for both types of loadings. However, for cyclic loads, negative shear capacity is observed may be due to the loss of bond between the stirrup and concrete is observed. The beams with welded reinforcement grids show satisfactory stiffness and ultimate capacity results compared to conventional stirrups. Low shear reinforcement ratio beams are much influenced by weld affecting beam deformability. It is stated that 0.63% of the shear reinforcement ratio is mandatory to avoid any weld failure.

Al Nuaimi et al. (2020): Investigated the durability behavior of reinforced concrete beams strengthened using Medium galvanized Steel Mesh(MSM) and High density galvanized Steel Mesh(HSM). These were tested under sunlight and saline water and tested for 6,12,24 months. The results indicate that beams strengthened with MSM and HSM showed 51% and 62% increases in load-carrying capacity observed at 28 days and 82% at two years. A delay of crack initiation is observed for exposed beams under sunlight and saline water. The first crack load increased to 84% compared with conventional beams. Hence high strength mesh and medium strength mesh proved to be better durability structural materials.

Abadel, (2021): Studied the shear capacity of reinforced concrete beams using four different strengthening techniques to enhance its capability. One of the strengthening techniques is welded wire mesh near the surface mounted. The RC beams with welded wire mesh as a strengthening technique were tested under a four-point bending setup. Compared with the control beam such as regular conventional stirrups and shear deficient beams. The Near surface mounted-welded, wire mesh strips show a 43% to 56% load increase compared to shear-deficient beams. The shift of failure mode is observed from shear failure to elastic failure. In addition to increased shear capacity, failure modes shifted from brittle shear failure to ductile flexural failure with increased stiffness of strengthened RC beams

Al-Rousan, R.Z., (2021) : Developed a novel application to evaluate the shear capacity of RC beams both before and after they were subjected to elevated temperatures and used WWM as internal shear reinforcement. The study parameters were: the WWM layers, the area, and the levels of elevated temperatures. The ultimate strength, deflection, stiffness, and toughness of the structure were all measured and recorded in the study. The findings obtained indicate that the shear capacity of RC beams subjected to high temperatures was significantly increased by the internally mounted WWM.

Alhoubi, Y. et al (2023): Studied to determine the feasibility to withstand the shear load effect by employing Welded Wire Reinforcement (WWR) that has been cold-formed into the shape of a closed steel cage. The study took into account various factors like transverse steel reinforcement ratios, shear span-to-thickness ratios, grid apertures, and wire sizes. The test results of stirrup-reinforced beams and WWR-reinforced beams were compared with respect to stiffness, shear strength, residual strength, ductility, and crack development characteristics. It concluded that the WWR-reinforced beams had shear strengths of 2 to 17% greater than those of the similar stirrup-reinforced beams.

2.5 Numerical simulation RC using ABAQUS

One of the influential finite element analysis software named ABAQUS which is widely used in engineering and research for simulating and analyzing various structural and mechanical systems, including reinforced concrete structures.

Grassl et al. (2013): Developed a constitutive model to examine concrete structure failure considering the principles of damage and plasticity mechanisms. The failure mechanism is studied for the load taken as a multiaxial loading application which is obtained by merging the effective stress plasticity and damage models. The above two models are based on strain measures of plastic and elastic condition. The combined Concrete Damage Plasticity Model, CDPM2, was obtained with a combination of stress-based plasticity and strain-based damage model. The changeover from tensile to crushing failure is identified from this model. This advantage is achieved by introducing the isotropic damage variables for tension and compression. This model also gives mesh-independent load-displacement curves for tension and compression failure.

Genikomsou & Polak (2015): Developed a numerical model for slab column connections using nonlinear finite element analysis. The loadings of static and pseudo-dynamic cases are analyzed, and their failure patterns and ultimate load are studied. The model was developed in 3D Finite Element Analysis using ABAQUS software with different modules executed, including the element size and mesh. Dilation angle and other damage parameters are important material parameters identified to get an accurate required model. Another module that plays a prominent role in finite element analysis is discretization by performing mesh module and mesh sensitivity analysis, which is a critical step to get a mesh-dependent module. The developed model is verified with experimental results.

Farahmandpour et al. (2017): Developed a damage plasticity model for concrete columns retrofitted with Fiber-Reinforced Polymer(FRP). The developed model is a column that needs sensitivity confinement analysis. Material properties like dilation characteristics and confinement sensitivity, unilateral effect in cyclic loading and damage due to microcracking is considered under triaxial stress condition. A new parameter named the cam-clay type function is introduced to predict the dilation behavior. The additional feature of confined concrete can be reproduced in both active and passive confined concrete forms.

Earij et al. (2017): Developed a model of the dynamic behavior of reinforced concrete beams under four-point loading using 3D nonlinear finite element analysis combined with a concrete damaged plasticity model. The beam is loaded under four-point bending, and flexural characteristics are studied. In executing dynamic characteristics, the beams loading, unloading and reloading are performed, and crack patterns are identified. While performing analysis, the perfect bond between steel bars and concrete is established; thereby, bond-slip characteristics and crack patterns are modelled. Mesh sensitivity verified by a provided structured mesh of 8-

noded elements and an unstructured mesh of linear 4-noded and quadratic 10-noded tetrahedral elements are considered. It is stated that huge differences are not found with the variation of different element types. But differences are observed in crack patterns developed by different elements; many cracks are developed for finer meshes.

Hany et al. (2016): Developed a modified concrete damage plasticity model for the applications of columns of different cross sections like rectangular, circular and square and for concrete strengths varying from normal to high. It is stated that there are a few limitations in the Concrete Damage Plasticity Model(CDPM) and creating restrictions to develop all types of models, especially for confined concrete. A new modified CDPM is developed in this aspect, which gives accurate results. In this model, both strain hardening / strain softening relations are established for both confined and FRP-confined concrete are developed.

Rewers, (2019): Developed a numerical model using Finite Element Analysis(FEA) software of ABAQUS for a reinforced concrete beam with high-strength steel applied with a four-point bending load. This model is developed using the Concrete Damaged Plasticity Model(CDPM) and developed material properties like dilation angle. It is stated that a dilation angle greater than 25 degrees gives accurate results. In contrast, a dilation angle with lower values does not produce consistent results to formulate the actual behavior of the concrete beam. Based on this observation, dilation angle values were developed for the developed model. In this CDP model, the dilation angle property is set using three ways according to our requirements. These three ways of this property are listed as stress-displacement, stress-cracking strain and from fracture energy mechanism. Another parameter focused on developing the model is the load application, either by force control or displacement control. Even mesh sensitivity is verified with different types of meshes with varying densities considering the effect of shear reinforcement.

Huang et al. (2019): Developed a numerical model of two-dimensional nonlinear finite elements of reinforced concrete beams of I-sections. The aim of developing this model is to predict the post-shear crack behavior of selected members. The obtained numerical model results were validated with experimental output results as total and shear deflection, average shear and vertical strain and principal strain slope. The experimental results are monitored by the Digital Image Correlation(DIC) verified by the above finite element model. This model correlates well with experimental data and is more accurate than the other FE models, like the rotating crack model and response-2000.

Lee. et al. (2020): Modelled a post-tensioned concrete beam using finite element analysis software ABAQUS considering the Concrete Damaged Plasticity model(CDP). The CDP model also has the advantage of predicting the results of the member's stress, deflection and strength.In this inelastic nonlinear characteristics are considered. In the CDP model, the main variableslike dilation angle, flow potential eccentricity, and the ratio of biaxial and uniaxial compressivestrength are studied and executed. Also, additional parameters like a ratio of second stress invariant on the tensile meridian to the compressive meridian and the viscosity parameter are used to analyze the model. The crack patterns obtained are based on the tensile deformations developed in the concrete beam. Numerical results obtained from this model are highly correlated with experimental results.

Minh et al. (2021): Developed an inventive concrete damage plasticity model for high grade strength concrete beams simulating static and dynamic loadings. This model is obtained from the fundamentals of Concrete Damage Plasticity (CDP) using ABAQUS software. This CDP model is mainly preferable because of the damage parameters like tensile and compressive damage variables relating to the stress-strain curves of tensile and compressive behavior. Mesh sensitivity is verified using different mesh sizes. Dynamic increase factor is used to determine dynamic characteristics, taken from MODEL 2010 Code is used to arrive at the strain rate due to the compressive strength of concrete. Thus, a new concrete damage plasticity model produces precise results correlating to the experimental results.

Megarsa & Kenea (2022): Developed the numerical model to study the shear behavior of ferrocement beams using wire mesh and compared it with normal beams with equal weight ratio using ABAQUS 6.14. The developed ferrocement beams using wire mesh are preferred because of the material advantages like it is cheap construction material and performs better than regular steel reinforcement. The Parameters like ultimate load, shear capacity and stiffness are evaluated considering variables like the diameter of the wires, spacing of the wires and number of mesh layers used. The numerical simulation was performed using the concrete damaged plasticity model because it was able to consider the non-linearity in terms of geometry, and material results stated the relation of variables with respect to parameters. As the diameter and spacing of wire mesh decreases, the ultimate failure, shear capacity and stiffness increase. When the number of mesh layers increases, resulting from increasing in the parameters like ultimate failure load, shear capacity and stiffness of beam, but it limits to three numbers, exceeding this, no other change is observed. The numerical results using ABAQUS indicate a highly correlated with experimental results.

2.6 Summary of literature review

1. Strut-and-Tie Model (STM), Modified compression field theory (MCFT) are two basic theories explain the shear behavior of RC beams. Further extensions of basic models, upper-bound plasticity models, shear panel models, artificial intelligence models, and numerical

models came forward to explain the shear behavior of RC beams in better way.

2. Different theories and codes identified the variables that effect the shear strength of the RC beams with and without web reinforcement are shear span-to-effective depth ratio, compressive strength, flexural reinforcement ratio, aggregate size, concrete cylinder strength, effective length-to-depth ratio and a beam size.
3. The ultimate shear strength is determined by various methods using artificial neural networks and assessing the shear components separately shear resistance due to web reinforcement(Vs) and shear resistance due to concrete(Vc). This shear strength is enhanced using different strengthening technique with numerous materials.
4. Welded Wire Mesh (WWM) termed as welded wire fabric has been used in wide applications in bridge decks, roads and in structural members like beams and slabs. It was used to study the tensile strength and ductility, bond strength, fatigue behavior, anchorage and as near surface shear reinforcement. It enhanced the ultimate strength of the member both as flexural and shear, improved ductility, deflection and stiffness parameters.
5. New shear reinforcements are developed other than regular stirrups are swimmer bar, Insulated stirrups, lateral stirrups and continuous spiral rectangular transverse reinforcement to enhance the shear capacity.
6. Reinforced Concrete beams are analyzed in ABAQUS using Concrete Damaged Plasticity model (CDP) and the main variables like dilation angle, flow potential eccentricity, ratio of biaxial and uniaxial compressive strength is required. Mesh sensitivity can be verified by different structured and unstructured meshes using n-noded elements to get accurate results. This model can predict post shear crack behavior, tension and compression failure.

The published literature specifically on the use of welded wire mesh as transverse reinforcement replacing conventional stirrups and its effect on the shear strength of concrete beams is scant.

2.6.1 Research gaps identified

The following major gaps in the literature were identified:

1. The core zone of the RC beam members was un-reinforced, resulting in the absence of any resistance to the propagation of shear cracks.
2. The WWM has been used in reinforced concrete in several ways but not as a core zone reinforcement in providing shear resistance.

Hence in the following chapters, the investigation related to the study of the shear behaviorof RC beams provided with welded wire mesh as a core zone shear reinforcement and compareand quantify the same with the shear performance of RC beams provided with regular stirrups is presented.

Chapter 3

SCOPE AND OBJECTIVES OF THE INVESTIGATION

Chapter 3

SCOPE AND OBJECTIVES OF THE INVESTIGATION

3.1. Research Significance

In general, the Reinforced Concrete (RC) beams subjected to transverse loading create non-uniform bending accompanied by internal shear forces. With the result the reinforced concrete beam cross-section experiences the normal and flexural shear stresses. The distribution of flexural shear stress across the depth of the transverse section relies on the shape of the cross section. In the rectangular cross sections, the flexural shear stress is distributed non-uniformly throughout the depth of the cross section. In homogeneous rectangular cross sections, the intensity of flexural shear stress becomes zero in the outer edges and reaches maximum at the neutral axis i.e near the core zone of the cross section as shown in Fig.3.1.

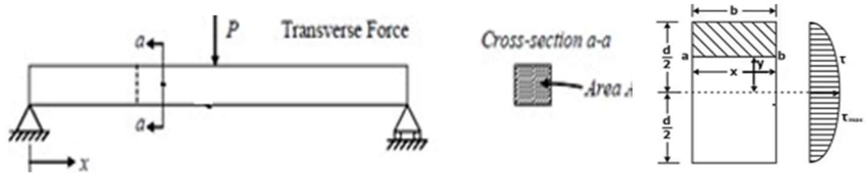


Fig.3.1 Shear Stress distribution across the rectangular homogeneous Beam Cross Section

The main modes of shear failure in reinforced concrete beams are characterized by the formation of diagonal cracks in the shear regions. At present the Reinforced Concrete (RC) - vibrated or self-compacting concrete, elements are provided with rectangular Stirrups (having required diameter, spacing and number of vertical legs) for resisting shear force (Fig.3.2).

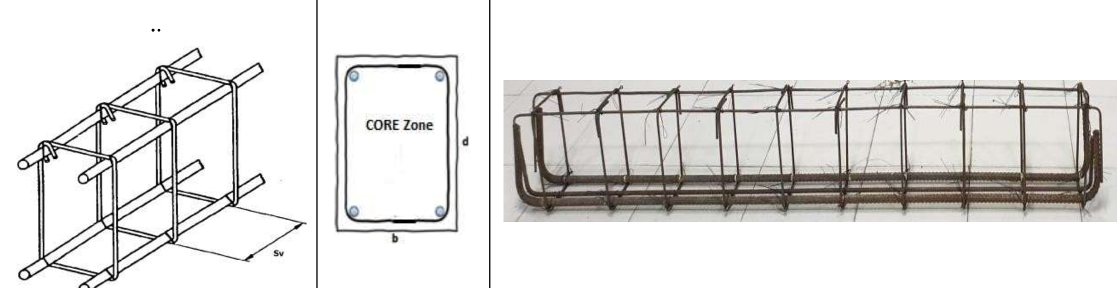


Fig.3.2 Reinforcement cage and cross section with conventional Stirrups

These stirrups go around near to the periphery. This kind of placement of stirrups in reinforced concrete beams leaves the central portion of the transverse section where there is presence of huge transverse stress (shear stress), unreinforced. The present practice of using stirrups/ties cannot reinforce the core zone of the RC cross section. It is expected that sudden appearance of brittle failure and crack propagation is due to the discrete arrangement of stirrup leaving core zone and unable to provide resistance against diagonal tension. Hence, a hypothesis is made that by providing any form of effectively anchored reinforcement in the core zone (termed as core zone reinforcement) that intersects these shear cracks will improve the performance of RC members under the influence of transverse stresses.

Keeping the hypothesis in mind, a novel means of resisting shear and simultaneously enhancing the performance of Reinforced concrete members providing a prefabricated mesh such as Welded wire mesh (WWM) as a core zone reinforcement is presented in this investigation. The welded wire mesh is used either as transverse reinforcement replacing totally the conventional stirrups (Fig.3.3) or as longitudinal core zone reinforcement along with conventional rectangular stirrups /ties (Fig.3.4). The weld mesh either placed transversely or longitudinally in the core zone provides resistance against diagonal tension due to shear.

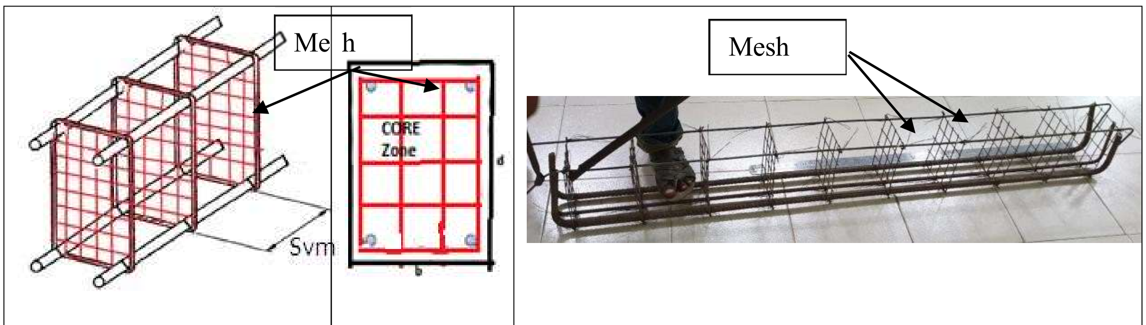


Fig.3.3 Reinforcement cage with Mesh as transverse reinforcement replacing the conventional stirrups and its cross section

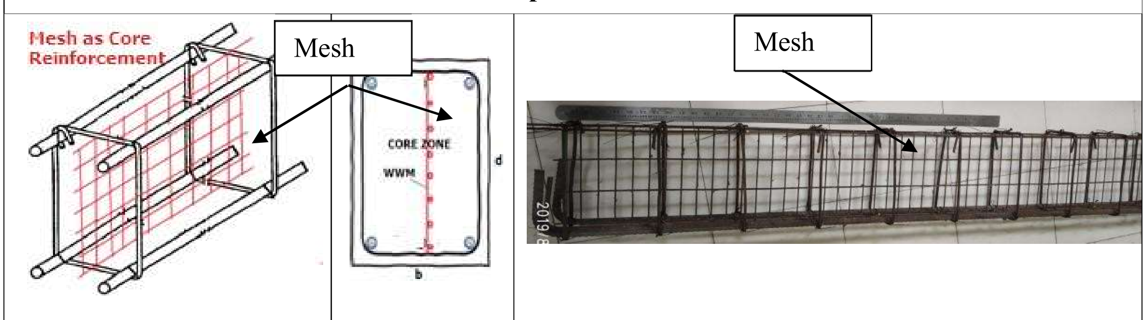


Fig.3.4 Reinforcement cage with mesh as longitudinal core reinforcement apart from stirrups and its cross section

3.2. Objectives of the investigation

In the present investigation, a study on the performance of RC beam wherein the welded wire mesh is used as a core zone reinforcement is taken up with an objective to answer the following questions:

1. What is the efficacy of the core zone reinforcement in the form of Welded Wire Mesh (WWM) used either as transverse reinforcement replacing totally the use of conventional stirrups or as longitudinal core reinforcement apart from conventional rectangular stirrups, in improving the performance of RC beam in shear?
2. How to quantify the effect of using WWM as a transverse reinforcement replacing totally the use of conventional stirrups in RC beams with a fixed shear span to depth ratio?
3. What is the effect of WWM as a transverse reinforcement replacing totally the use of conventional stirrups on the behavior of RC beams with different shear span to depth ratios?
4. How the shear strength obtained through the numerical analysis of RC beams provided with welded wire mesh as shear reinforcement using ABAQUS compare with the experimental shear strength?

An attempt is made to answer the above questions by setting the following FOUR different objectives and conducting the investigation in FOUR different phases.

Objective-I: A study on the efficacy of the welded wire mesh as a core zone reinforcementon the behavior of RC beams.

Objective-II: A study on the effect of welded wire mesh as a core zone transverse reinforcement.

Objective-III: A study on the effect of welded wire mesh as a core zone transverse reinforcement on the behavior of RC beams with varying shear span to depth ratio

Objective-IV: Numerical investigation using ABAQUS on the effect of welded wire mesh as a transverse shear reinforcement.

The total program of investigation is presented in Fig 3.5 which gives complete scope of the investigation.

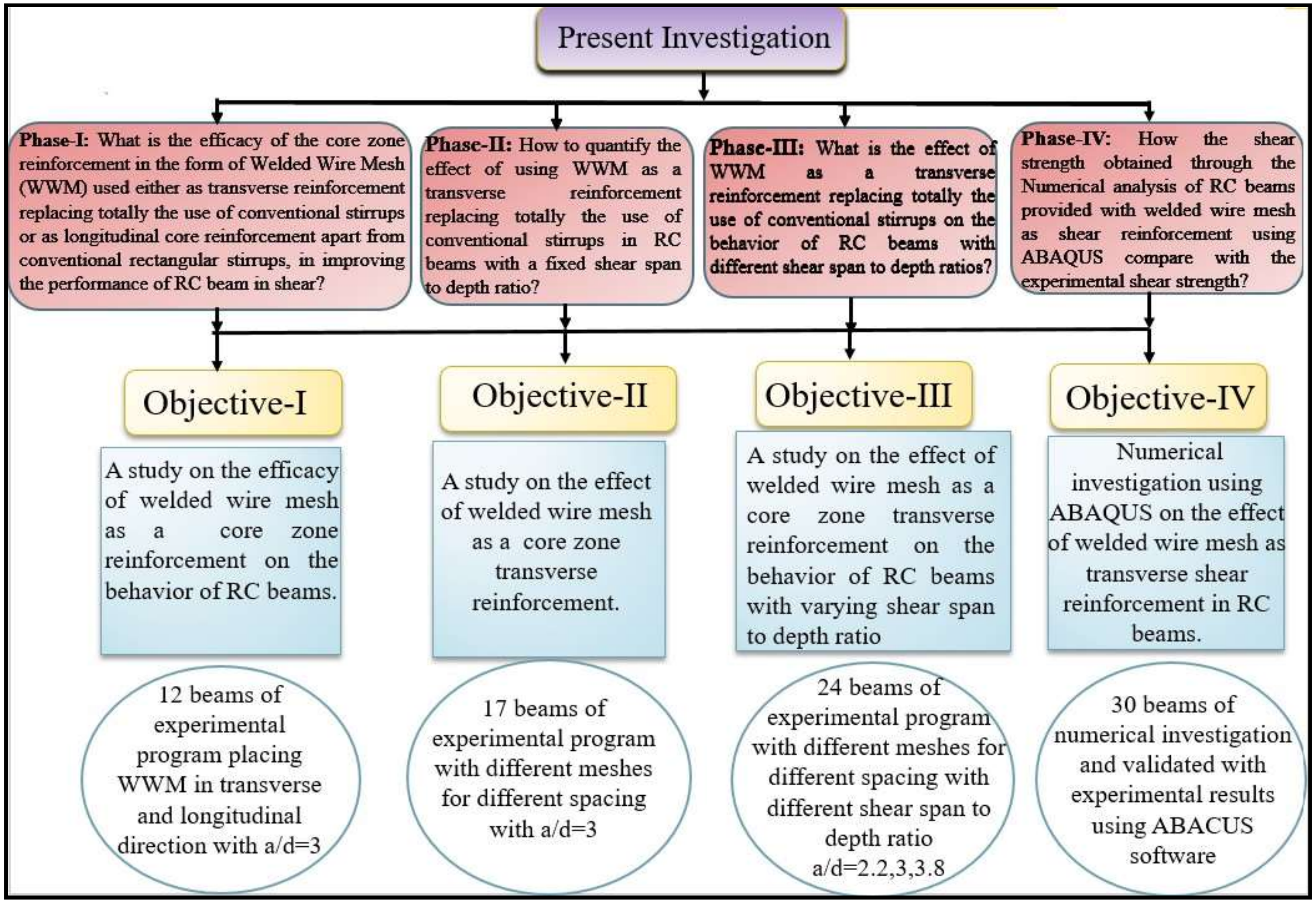


Fig. 3.5 Pictorial representation of program investigation

Chapter 4

A STUDY ON THE EFFICACY OF THE WELDED WIRE MESH AS A CORE ZONE REINFORCEMENT ON THE BEHAVIOR OF RC BEAMS

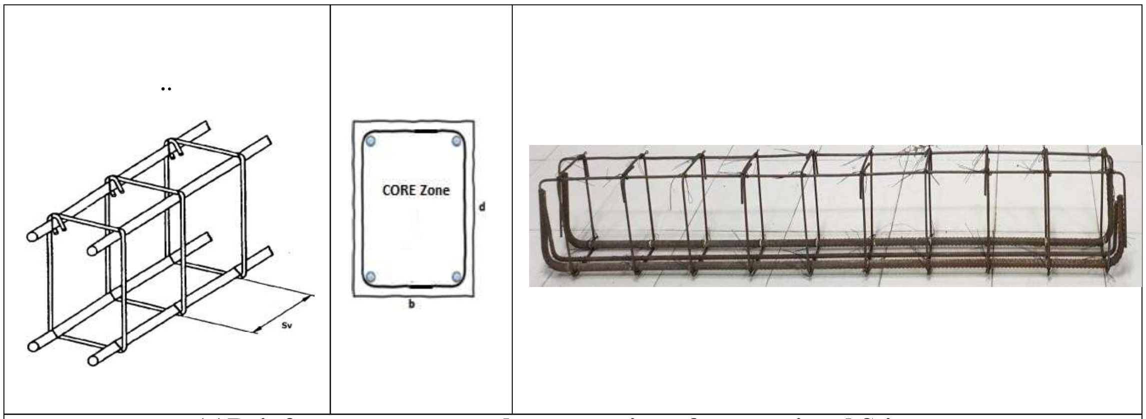
Chapter 4

A STUDY ON THE EFFICACY OF THE WELDED WIRE MESH AS A CORE ZONE REINFORCEMENT ON THE BEHAVIOR OF RC BEAMS

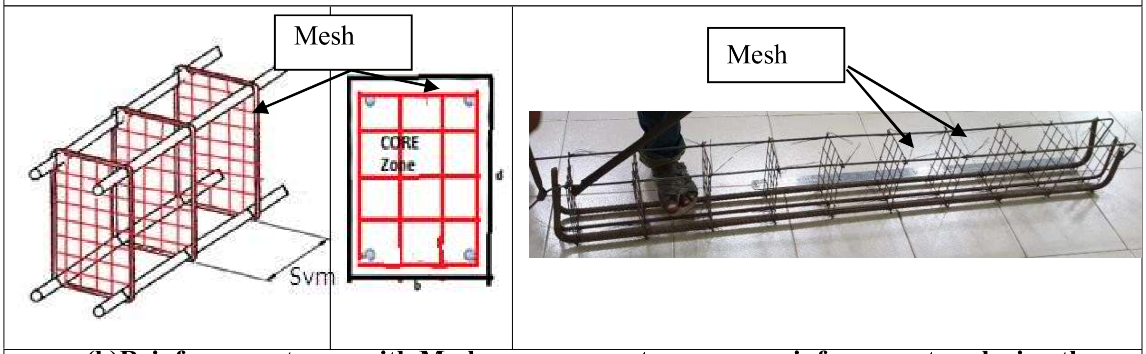
4.1 Experimental Program

In this Investigation, a novel means of resisting shear and simultaneously enhancing the performance of Reinforced concrete members by providing a prefabricated mesh namedWelded wire mesh (WWM) by way of core zone reinforcement is presented. There are two ways of reinforcing the core zone with WWM i.e., one way is to use the WWM as a transverse reinforcement in the core zone and the other way is to use the WWM as a longitudinal reinforcement in the core zone. Hence the experimental program was carried out by cast and testing of RC beams in two batches, each batch representing the way in which the WWM used as a core zone reinforcement. The aim of the investigation is to answer to the question: 'What is the efficacy of the Welded Wire Mesh (WWM) used either as transverse reinforcement in the core zone replacing totally the use of conventional stirrups or as longitudinal reinforcement in the core zone apart from conventional rectangular stirrups, in improving the performance of RC beam in shear?'.

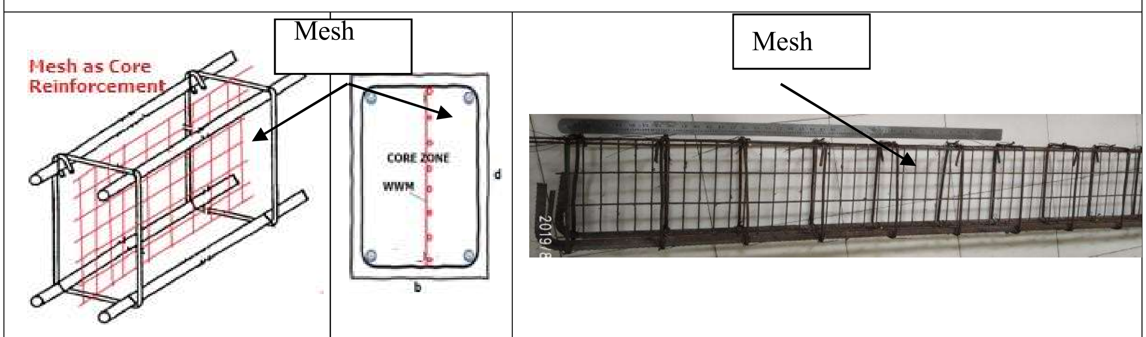
The experimental program consists of casting and testing of fourteen numbers of Reinforced concrete (RC) beams. These fourteen RC beams were cast and tested in two batches. In the first batch, seven RC beams were tested to study the efficacy of the WWM as core zone transverse reinforcement replacing totally the use of conventional stirrups. In the second batch, seven RC beams were tested to assess the effectiveness of WWM used as a core zone longitudinal reinforcement apart from conventional rectangular stirrups which affecting the behavior of RC beams in shear. The flexural steel adopted was maintained constant in all the RC beams tested. The adopted shear span to effective depth ratio for all the beams is three. All the beams were tested under two-point loading. The typical types of the reinforcement cages used are illustrated in Fig.4.1



(a)Reinforcement cage and cross section of conventional Stirrups



(b)Reinforcement cage with Mesh as core zone transverse reinforcement replacing the conventional stirrups and its cross section



(c) Reinforcement cage with mesh as core zone longitudinal reinforcement apart from stirrups and its cross section

Fig. 4.1 Types of Reinforcement cages used in the experimental program

4.2 Scheme of Experimental work

4.2.1 I-Batch: WWM as core zone transverse reinforcement

The experimental program consists of cast and testing of seven numbers of Reinforced Concrete (RC) beams tested under symmetrical two-point loading (i.e Four-point bend test). Out of seven numbers of RC beams, the first beam designated as C100 has only longitudinal steel without any Stirrups in maximum shear zone i.e. near supports. However, the central flexure zone of C100 beam has both longitudinal steel and stirrups at 100 mm c/c so that there is no premature failure due to flexure. The C100 beam is meant for assessing the shear strength of RC beam without any stirrups in the shear zone.

The remaining six beams are divided into two sets. The first set consisted of three RC beams (R160, R100 and R60). In the first set of RC beams, the variable parameter was the spacing of stirrups i.e. the conventional stirrups (2 legged 6Φ) are used as shear reinforcement at spacing of 160mm, 100mm and 60mm respectively. The second set of three RC beams (M160, M100 and M60) consisted of welded wire mesh as transverse reinforcement replacing totally with conventional stirrups. The spacing of weld mesh as transverse reinforcement along the span of the RC beam adopted includes 160mm, 100mm and 60mm. The diameter of weld mesh wire is 2.34 mm, spacing of wires is 50mm vertical and 30mm horizontal. The spacing of wires in the weld mesh is chosen so as, not to cause any hindrance to the flow of concrete. Each RC beam specimen cast and tested was designated by the type of transverse reinforcement adopted (i.e Stirrups (R)/ Mesh (M)) and the spacing of transverse steel. Thus, the RC beam specimen whose designation is M60 stands for RC beam provided with welded wire mesh at 60 mm spacing as transverse reinforcement. The volume (or) weight of transverse reinforcement in the form of weld mesh in the RC beam M160, M100 and M60 beams is roughly about half of the volume (or) weight of transverse reinforcement in the form of stirrups used in the RC beam R160, R100 and R60 respectively and the beams details are given in Table 4.1 and transverse welded wire mesh is shown in Fig.4.2. Hence the RC beams provided with weld mesh in place of conventional stirrups astransverse reinforcement consumed less volume or weight of steel for a given spacing of transverse reinforcement. The longitudinal steel adopted was maintained constant in all the seven RC beams tested. The control beam R160 is specifically designed to fail in shear by adopting the spacing of stirrups as 160 mm against the required design spacing of 140mm. Theshear span to effective depth ratio adopted for all the beams is 3. The size of the RC beams adopted is 140 mm width, 240mm overall depth and 1650mm in length. Along with the RC beams, the concrete cubes of standard size (150mmx150mmx150mm) were cast and tested toascertain the concrete compressive strength. The reinforcement cages used are shown in Fig.4.3.

Table.4.1 Details of Core Zone transverse reinforcement beam specimens tested

S.No.	Beam	Details of RC beam Cross Section and Longitudinal Reinforcement	Transverse Reinforcement: Details	Transverse Reinforcement: Vol. Percent of Transverse steel per unit length of beam	Transverse Reinforcement: Total Number & Wt. of Trans. Steel N(Wt. in kg)	Total Wt. of Reinf. Cage (kg)
1	R160	b x D x L: 140 x 240 x1650 mm Tension Reinf. 2-12Φ & 1-16Φ Comp. Reinf: 2-6Φ Total Wt. of Long. Reinf per RC beam: 7.55 kg	2 Lgd 6Φ @160 c/c	0.157	10(1.21)	8.76
2	R100		2 Lgd 6Φ @100 c/c	0.252	16(1.92)	9.47
3	R60		2 Lgd 6Φ @60 c/c	0.421	26(3.12)	10.67
4	M160		WWM @160 c/c	0.085	10(0.53)	8.08
5	M100		WWM @100 c/c	0.136	16(0.88)	8.43
6	M60		WWM @60 c/c	0.226	26(1.43)	8.98
7	C100		No Stirrups in maximum shear zone i.e. near supports. Six numbers of stirrups are provided only in middle 500 mm length at 100 c/c. Two more stirrups, one at each end of the beam		8(0.96)	8.51

Concrete
Compression Strength= 31.8 MPa

Longitudinal Reinforcement
Yield Strength = 424 MPa
Ultimate Strength = 538 MPa

Transverse Reinforcement
Yield Strength = 285.6 MPa
Ultimate Strength= 361 MPa
Average weight of each stirrup = 0.12 kg
Diameter of Stirrup bar = 5.1 mm

WWM: Welded Wire Mesh
Wire dia= 2.34mm Φ,
Spacing of wires:
Vertical=50mm, Horizontal=30mm,
Yield strength of Wires= 267.7 MPa,
Ultimate Strength of Wires = 347 MPa.
Average weight of each mesh = 0.055 kg

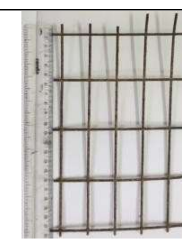
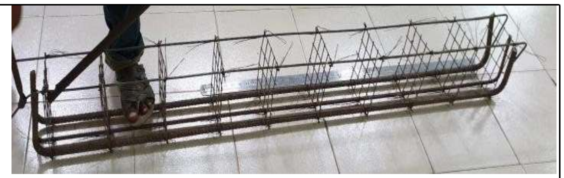
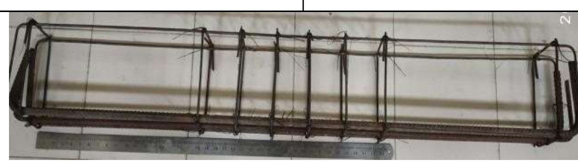


Fig.4.2 Transverse core zone WWM

	
R60	**M60**
	
R100	**M100**
	
R160	**M160**
	
C100	
Fig. 4.3 I-Batch: Reinforcement cages	

4.2.2 II-Batch: WWM used as a core zone longitudinal reinforcement

The experimental program involves the casting and testing of seven numbers of Reinforced Concrete (RC) beams. Out of seven RC beams, the first beam designated as C100 has only longitudinal steel without any stirrups in maximum shear zone i.e. near supports. However, the central flexure zone of C100 beam has both longitudinal steel and stirrups at 100 mm c/c so that there is no premature failure due to flexure. The C100 beam is meant for assessing the shear strength of RC beam without any stirrups in the shear zone.

In the remaining six beams, the first RC beam designated as L0 in which there are no stirrups but consisted of a longitudinally placed welded wire mesh in the middle of the core zone. The purpose of this beam is to know the functioning of WWM as a longitudinal core zone reinforcement alone in resisting shear without any stirrups. The second beam is control RC beam (designated as R160) in which the shear reinforcement consists of conventional stirrups. The control beam is specifically designed to fail in shear by adopting the spacing of stirrups as

160 mm against the required design stirrup spacing of 140mm. The remaining four beams (L160, L180, L200 and L265) consisted of welded wire mesh placed longitudinally in the middle of the core zone of the cross section apart from conventional stirrups. The parameter varied among these four RC beams is the spacing of conventional stirrups. The spacing of stirrups adopted includes 160mm (0.60d), 180mm (0.68d), 200mm (0.75d) and 265mm (d), where 'd' is the effective depth of the RC beam. The spacing of wires in the weld mesh is chosen so as not to cause any hindrance to the flow of concrete. There is small increase in the total weight of steel consumed in using the welded wire mesh as longitudinal core zone reinforcement along with stirrups. Each RC beam specimen cast and tested was designated by the type of transverse reinforcement adopted (i.e Stirrups (R)/ Mesh (L)) and the spacing of transverse steel. Thus, the RC beam specimen whose designation is R160 stands for RC beam provided with stirrups at 160 mm spacing as transverse reinforcement. The RC beam specimen whose designation is L200 stands for RC beam provided with welded wire mesh as longitudinal core zone reinforcement along with conventional rectangular stirrups at 200mm spacing along the length of the beam.

The size of the RC beams adopted is 140mm width, 300mm overall depth and 1650mm in length. Three concrete cubes (150mmx150mmx150mm) were cast and tested along with each specimen to determine the concrete compressive strength. The details of specimens tested are given in Table.4.2 and longitudinal welded wire mesh is shown in fig Fig. 4.4. The reinforcement cages used are shown in Fig.4.5

Table 4.2 Details of Core zone longitudinal reinforcement Beam Specimens

S.No	Beam	Size of the Beam and Effective depth (mm) And reinforcement	Core zone Reinf. (Long) and its Wt.		Stirrup Reinforcement			Total Wt. of Trans Steel (Stirrups + WWM) (kg)	% increase in total Trans Steel*
			WWM	Wt.(kg)	Spacing (mm) (in terms of effective depth)	Total No. of Stirrups in the beam	Total Wt. of Stirrups (kg)		
1	R160	b x D x L: 140 x 300 x1650 mm Effective Depth = 265mm Tension Reinf. 2-12Φ & 1-16Φ Comp. Reinf: 2-6Φ	--	--	160 (0.60d)	11	1.54	1.54	--
2	L160		WWM	0.547	160 (0.60d)	11	1.54	2.087	35.5
3	L180		WWM	0.547	180(0.68d)	10	1.40	1.947	26.4
4	L200		WWM	0.547	200 (0.75d)	9	1.26	1.807	17.3
5	L265		WWM	0.547	265 (d)	7	0.98	1.527	-0.84
6	L0		WWM	0.547	-	2 (ends)	0.28	0.827	-46.2
7	C100		No Stirrups in maximum shear zone i.e. near supports. Six numbers of stirrups are provided only in middle 500 mm length at 100 c/c. Two more stirrups, one at each end of the beam.			8 (6+ One each at the ends of the beam)	1.12	1.12	27.3

Concrete
Compression Strength= 27.5MPa

WWM : Welded Wire Mesh
Wire dia=2.16mm Φ,
Spacing of wires: Vertical=80mm, Horizontal=30mm,
Yield strength of Wires= 267.7 MPa,
Ultimate Strength of Wires = 347 MPa
Nominal mass per square meter = 1.316 kg
Size of Longitudinal mesh = 0.260 x 1.60 = 0.416 sqm
Wt. of Longitudinal mesh = 0.416 x 1.316 = 0.547 kg

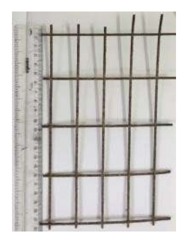
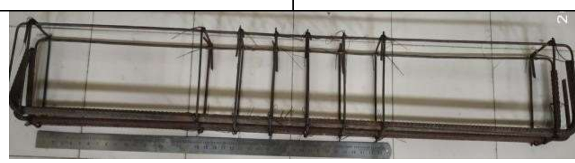


Fig.4.4 longitudinal core zone WWM

Longitudinal Reinforcement
Yield Strength = 424 MPa
Ultimate Strength = 538 MPa
Transverse Reinforcement
Yield Strength = 285.6 MPa
Ultimate Strength = 361 MPa
Wt of each stirrup= 0.14 kg

	
R160	**L0**
	
L160	**L180**
	
L200	**L265**
	
C100	
Fig.4.5 II-Batch: Reinforcement cages	

4.3 Materials used

The materials preferred in this experimental program consist of ordinary Portland cement of 53 grade, the river sand as fine aggregate, the coarse aggregate of 20mm nominal size, the potable water and the super plasticizer.

Cement: Ordinary Portland cement (OPC) 53 grade confirming to IS 269-2015 is used in this investigation and it is stored properly. Basic preliminary investigation was made before using the cement. Further the laboratory tests was conducted like fineness of cement confirming to IS 383-1970, Initial and final Setting times along with its consistency confirming to IS:4031(Part 4):1988, Specific gravity of cement confirming to IS 2720 (Part 3). The Cement Properties are listed in Table.4.3

Table 4.3 Properties of Cement			
Fineness of Cement	3%	Initial setting time	120min
Consistency of cement	0.31P	Final Setting Time	450min
Specific Gravity of Cement	3.0 g/cm3		

Fine aggregate: Fine aggregate in compliance to Zone-II of IS: 383 (2016). Fine aggregate is taken as river sand which is air dried one is used in this experimentation. To assess its quality basic laboratory tests were like sieve analysis is conducted to confirm its zone with the fallowing sieves like 4.75mm, 2.36mm,1.18mm, 0.6mm, 0.3mm and 0.15mm and 0.075mm respectively presented in Table 4.4. Also, the specific gravity and density of fine aggregate is conducted confirming to IS 383-2016 and IS 2386-3(1963) respectively. The fineness modulusof the fine aggregates recorded as 2.55. The specific gravity and bulk density of fine aggregaterecorded as 2.65 g/cm^3 and 1.45 g/cm^3 respectively.

Table 4.4 Fineness modulus of Fine aggregate			
Sieve Size(mm)	**Weight retained(gm)**	**Cumulative Weight(gm)**	**Cumulative % weight retained**
4.75	0	0	0
2.36	18	18	1.8
1.18	148	166	16.6
0.6	350	516	51.6
0.3	172	688	68.8
0.15	312	1000	100
Total	1000		255
Fineness modulus 255/1000= 2.55			

Coarse Aggregate: Coarse aggregate of not more than 20mm nominal size is selected as it may create difficulty in the flow of concrete through mesh creating honey combs in the member. As coarse aggregate is the main element for development of strength in concrete, the physical properties like specific gravity of coarse aggregate, bulkdensity of coarse aggregate confirming to IS 2386(Part 3) and sieve analysis confirming to IS 383 is performed presented in Table 4.5. In concrete mix, coarse aggregate consists of 40% passing through 20mm and retained on 16mm sieve, 30% passing through 16mm and retained on 12.5mm and 10mm and remaining 30% is aggregate below 10mm is used. The fineness modulus of the coarse aggregates used is 6.97. The specific gravity and bulk density of fine aggregate recorded as 2.80 g/cm^3 and 1.5 g/cm^3 respectively.

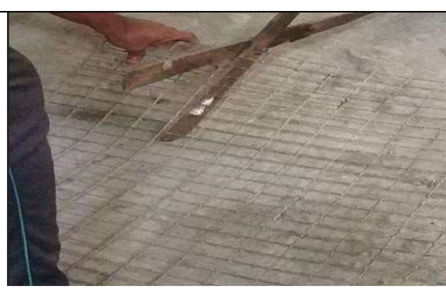
Table 4.5 Fineness modulus of Coarse aggregate			
Sieve Size(mm)	**Weight retained(g)**	**Cumulative Weight(g)**	**Cumulative retained %**
80	0	0	0
40	0	0	0
20	38	38	3.8
10	896	934	93.4
4.75	66	1000	100
2.36	0	1000	100
1.18	0	1000	100
0.6	0	1000	100
0.3	0	1000	100
0.15	0	1000	100
Total	1000		697.2
Fineness modulus	697.2/100=6.97		

Potable Water: Mixing and curing was done properly using potable water confirming as per IS 456-2000. The extent of water added in the concrete according to mix proportion fallowing the water-cement ratio.

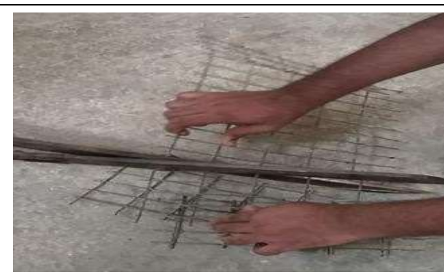
Super Plasticizer: Super Plasticizer chosen in this experimental program is to attain workability and Conplast SP430 of FOSROC chemical is preferred to attain the requirement. Nearly 0.5-0.7 percent to cement content is fallowed in the mix and the required slump is attained.

Steel reinforcement and Welded wire mesh:

The stirrups and the WWM used are shown in fig 4.5. The WWM of the required size is cut from the bundle of mesh are shown in Fig 4.6.



(a) Separation of mesh longitudinally from Original Mesh



(b) Separation of Transverse mesh from Original mesh

Fig. 4.6 Preparation of mesh from bundle mesh

	
(c) Fine grinding of Mesh edges	**(d) Finalized Transverse mesh**
Fig. 4.6 Preparation of mesh from bundle mesh	

			
(a) Regular conventional stirrup inRC beams of R60, R100,R160.	**(b) Regular stirrup in RC beams of L0, L160, L180, L200, L265.**	**(c) Core zone Transverse reinforcement mesh as completely replacing the stirrupin M60, M100, M160**	**(d) Core Zone Longitudinal reinforcement mesh in RC beams of L0, L160, L180, L200, L270**
Fig. 4.7 Regular, Transverse and Longitudinal shear reinforcements			

The details of the steel reinforcement and WWM used are given in Table 4.6.

Table 4.6 Welded wire Mesh Parameters Placed as Transverse and Longitudinal reinforcement along with Regular Stirrup

Position of Welded Wire Mesh	Mesh Parameters	Parameters
WWM Placed as Transverse Reinforcement mesh	Spacing of Vertical Wires	50mm
	Spacing of Horizontal Wires	30mm
	Diameter of Vertical wire	2.34mm
	Diameter of Horizontal wire	2.34mm
	Weight of One transverse mesh	0.055kg
WWM Placed as Longitudinal Reinforcement mesh	Spacing of Vertical Wires	80mm
	Spacing of Horizontal Wires	30mm
	Diameter of Vertical wire	2.16mm
	Diameter of Horizontal wire	3.86mm
	Weight of Longitudinal mesh per 160mm Length	0.057kg
Regular Conventional stirrup	Weight of One Stirrup	0.12 kg
	Diameter of Stirrup	5.1mm

4.4 Concrete mix proportion

Concrete grade of M25 as per IS456-2000 is selected to test this novel idea for regular constructions and the mix proportion was developed considering the slump of 100mm. The following are the mix proportion presented in Table 4.7.

Table.4.7 Materials used (per Cu.m) of Phase-I Beams

Concrete Grade	Mix Proportion	Quantity of concrete making materials Per Cu.m				
		Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)	SP* (kg)
M25	1: 1.8: 3.1 w/c 0.45	380	685	1180	170	2.7

*SP: Super plasticizer (SP 430, Make: Fosroc Chemicals).

4.5 Casting and Testing

For casting the RC beams the steel channel moulds of required size were used. Based on width of beam as 140mm and length of the beam as 1650mm and also considering depth as 300mm, a steel C-Channels are placed back to back and arranged by fallowing dimensions and tightened with fastenings. Separate Cover blocks of required size is provided underneath the reinforcement cage in the moulds to maintain the effective depth of the beam. Once the completion of mould arrangement, the materials along with water are blended according to proportions. After24 hours of casting, the beam specimens were de-moulded and water cured for a period of 28 days as shown in fig 4.6. The average room temperature and relative humidity measured duringthe period of curing were 35±2ºC and 75% are respectively under curing pond. After the completion of curing period the specimens were removed from the curing pond and kept underthe shade. A day before testing the cured beams were white washed and marked on it with pencilthe location of supports, the positions of deflection gauges during the test and kept ready for testing. Further a speckle pattern was marked on the side face to enable capture of strains for analysis in future using Digital Image Correlation (DIC) technique. The beams were tested under two-point loading (four-point bend test) after a curing period of 28 days, on the TINIUS– OLSEN testing machine of 2000 kN capacity. The deflection of the beam was measured usingLVDT and deflection dial gauges. The details of test setup were shown in Fig.4.8. Thedisplacement control loading was adopted by moving the loading cross head at 1 mm per minutei.e., equal to 1/1500 of Span per minute (JSCE SF4,1985). The testing was continued till the point of ultimate load or the test set up became unstable whichever is earlier. The cracks formedon the beams were noted and marked for comparison of crack pattern and nature of failure.

(a) Casting of Beams **(b) Curing of beams**

Fig. 4.8 Casting, Curing and Testing of Beams

(c)Experimental Test setup

(d)Testing of Beam

Fig. 4.8 Casting, Curing and Testing of Beams

4.6 Test results

The Table 4.8 gives the experimentally recorded failure loads (ultimate load) and maximum deflections of core zone transverse reinforcement and Table 4.9 represents experimentally recorded failure loads (ultimate load) and maximum deflections of core zone longitudinal reinforcement beams.

Table.4.8 Loads and Deflection values of Tested beams of core zone transverse reinforcement

SNo	Beam	At Service		At Ultimate		Nature of failure At Ultimate	Slope of Shear crack With vertical	
		Ps (kN)	ds (mm)	Pu (kN)	du (mm)			
1.	R160	91.30	4.73	136.92	7.10	Shear	60.3^0	Ave.Slope 61.76^0
2.	R100	107.60	4.60	161.50	13.2	Flexure	61^0	
3.	R60	113.7	5.10	170.50	13.5	Flexure	64^0	
4.	M160	92.03	3.64	138.85	6.43	Shear	66.9^0	Ave.Slope 68.16^0
5.	M100	121.03	5.46	181.55	12.7	Flexure	68.6^0	
6.	M60	137.40	5.61	206.14	13.3	Flexure	69^0	
7.	C100	78.15	2.2	117.25	4.3	Shear	61^0	--
Notation:	Ps = Load at Service, Pu= Load at Ultimate, ds= Deflection at Service, du =Deflection at Ultimate							

Table.4.9 Loads and Deflection values of Tested beams as core zone longitudinal Reinforcement							
S. No	Beam	At Service		At Ultimate		Nature of failure At Ultimate	Slope of Shear crack With vertical
		Ps (kN)	ds (mm)	Pu (kN)	du (mm)		
1.	R160	117.40	3.80	176.04	6.85	Shear	60.3^0
2.	L160	181.60	4.20	272.32	12.2	Flexure	57.6^0
3.	L180	163.90	4.80	245.85	13.2	Flexure	69.6^0
4.	L200	146.30	3.14	219.38	6.1	Flexure-Shear	70.9^0
5.	L265	121.10	5.46	181.55	11.2	Shear	71.5^0
6.	L0	115.90	2.38	173.98	3.22	Shear	60.9^0
7.	C100	98.10	1.85	147.25	3.98	Shear	61^0
Notation: Ps = Load at Service, Pu= Load at Ultimate, ds= Deflection at Service, du =Deflection at Ultimate, Allowable deflection at Service (as per IS 456:2000) = L/250							

4.7 Load deflection behavior of RC beams

4.7.1 Load Deflection behavior of transverse mesh

From the above results the observed ultimate load of the beam and corresponding spacing of transverse reinforcement (Mesh or Stirrups) in the beam is shown in Fig.4.9. The load deflection diagrams of all the tested beams were drawn and are presented in Fig. 4.10.

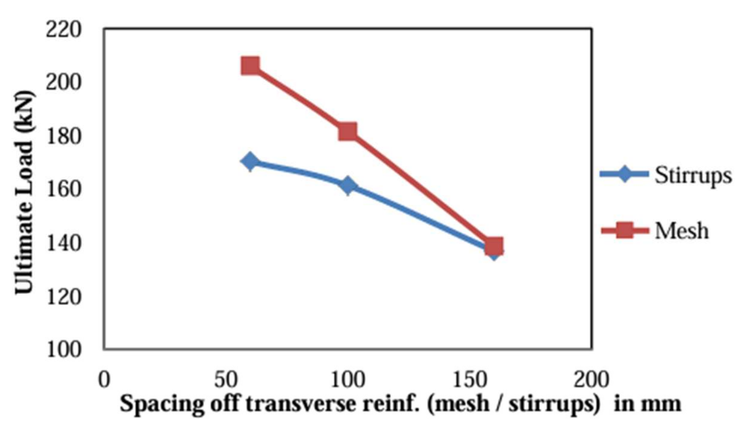


Fig.4.9. Ultimate Load vs Spacing of core zone transverse reinforcement (Mesh / Stirrups)

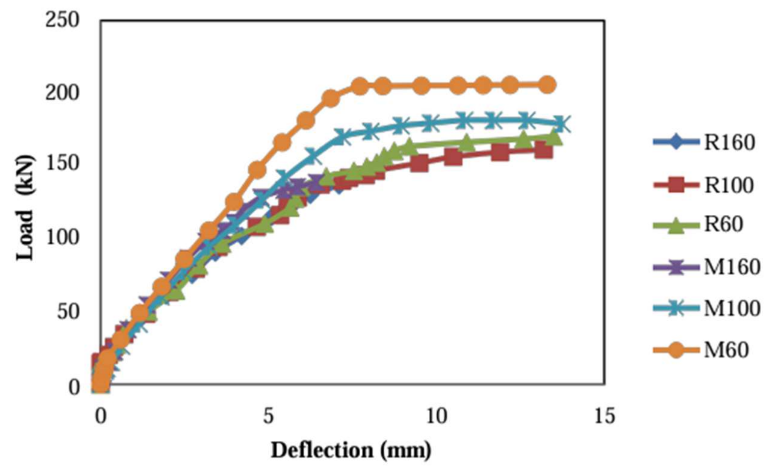


Fig. 4.10. Load deflection diagrams of Core Zone transverse reinforcement

4.7.2 Load Deflection behavior of longitudinal mesh

From the above results the observed ultimate load of the beam and corresponding spacing of transverse reinforcement (mesh or stirrups) in the beam is shown in Fig.4.11. The load deflection diagrams of all the tested beams were drawn and are presented in Fig. 4.12.

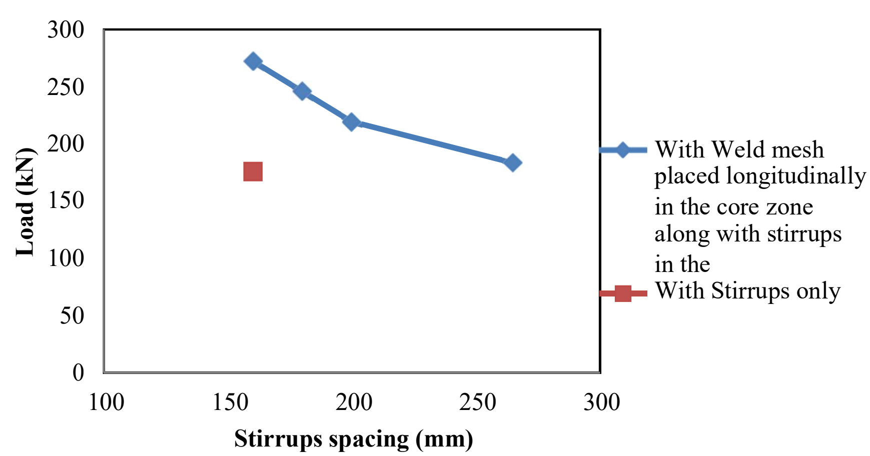


Fig. 4.11 Ultimate Load vs Spacing of core zone longitudinal reinforcement (mesh along with stirrups)

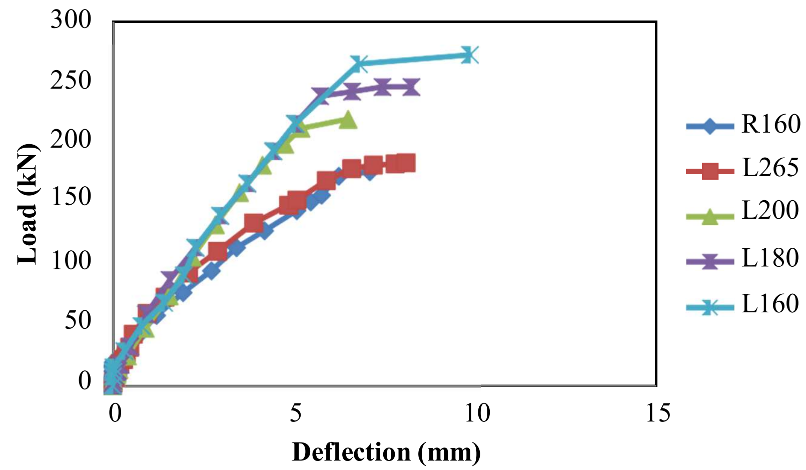


Fig. 4.12. Load deflection diagrams of core zone longitudinal Reinforcement

4.7.3 Failure Patterns

The failure Patterns of all tested beam specimens are shown in Fig.4.13

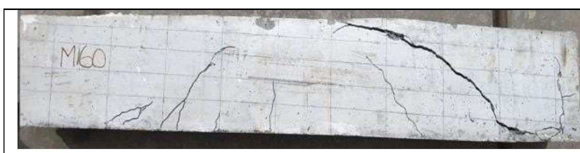
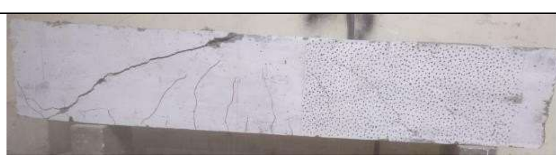
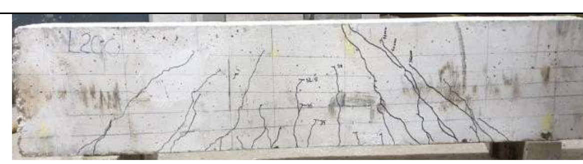
	
(a) : M160	**(b): R160**
	
(c): M100	**(d): R100**
	
(e): M60	**(f): R60**
	
(g): L265	**(h): L200**

Fig. 4.13 Failure patterns of longitudinal and transverse reinforcement beams

	
(i): L180	**(j): L160**
	
(k): L0	**(l): C100**

Fig. 4.13 Failure patterns of Longitudinal and Transverse Reinforcement beams

4.8 Discussion of behavior of RC beams provided with core zone reinforcement

4.8.1 RC beams with core zone transverse reinforcement:

The observations made during the testing indicated that the RC beam C100 having no stirrups in the shear zone and the RC beam R160 provided with conventional two-legged stirrups at 160mm c/c have failed by developing a major diagonal shear cracks (Fig 4.13(1) and Fig 4.13(b)) as expected because they were designed to be shear deficient. The propagation of the cracks was sudden when reaching the ultimate load. In the case of RC beam M160 having WWM in place of conventional stirrups, also failed in shear (Fig 4.13(a)). However, the ultimate (failure) load observed in both R160 and M160 beams is nearly same. In case of R100 and R60 beams wherein there is closer spacing of the stirrups, the ultimate load observed is more than that of R160. Further both R100 and R60 beams though the shear cracks have developed initially but have failed in flexure at ultimate by developing clear flexural cracks (Fig 4.13(d) and 4.13(f)). The RC beams M100 and M60 wherein the conventional stirrups are replaced bythe welded mesh, have also failed in flexure by developing a clear flexural crack near the mid span of the beams (Fig 4.13(c) and 4.13(e)) and also the crushing of compression concrete was noticed. However, the ultimate load of beams M100 and M60 observed are more than that of R100 and R60 respectively. As the spacing of web reinforcement (in the form of mesh / stirrups) reduced, the rate of increase of load in beams with weld mesh as core zone transverse reinforcement is observed to be more than that in beams with conventional stirrups. The Improvement in shear strength of RC beams with weld mesh as web reinforcement over that with conventional stirrups is ranged from 1.41% to 20.9% as the spacing of transverse reinforcement is reduced from 160mm to 60mm. The improvement in shear strength may be attributed to the effectiveness of mesh over conventional stirrups, in controlling / delaying the formation of shear crack.

The control beam R160 is specifically designed to fail in shear by adopting the spacing of stirrups as 160 mm against the required design spacing of 140mm. The other two beams R100 and R60, were provided with conventional stirrups at a reduced spacing and made the beams to fail in flexure. The experimentally observed behavior of beams indicated that the replacement of conventional stirrups with WWM, did not make any difference in the nature offailure i.e when R160 failed in shear the corresponding M160 also failed in shear. Similarly, when R100 failed in flexure corresponding M100 also failed in flexure. Similar is the case withR60 and M60. However, the ultimate load of the beams provided with WWM as core zone transverse steel in place of conventional stirrups at similar spacings have always indicated higher loads. At this point it is to be noted that the volume (or) weight of transverse reinforcement in the form of weld mesh used in the RC beams: M160, M100 and M60 is roughlyabout half of the volume (or) weight of transverse reinforcement in the form of stirrups used inthe RC beam R160, R100 and R60 respectively (as given in Table 4.1). Hence it can be concluded that for the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM will be able to provide similar or better performance of RC beams compared to that of RC beams having conventional stirrups. This clearly indicates the effectiveness and economy of WWM over the conventional stirrups. Further it can be concludedthat the nature / behavior of the RC beam remained more or less similar with the replacement of conventional stirrups with welded wire mesh as transverse reinforcement for the same spacing of transverse steel in the form of mesh / stirrups.

In general, the slope of the shear cracks (angle made by the shear crack with vertical, as shown in Table 4.1) in RC beams with WWM as transverse reinforcement is more (on an average by 50) than that with conventional stirrups. The increase in the slope of the shear crack indicates the effectiveness of mesh over conventional stirrups, in enhancing the shear strength. Further the ductility as indicated by the area under load deflection plot (Fig.4.10) is more in the case of RC beams with WWM by way of transverse reinforcement compared to the RC beams with conventional stirrups.

The observation of the deflections at service load i.e., at 0.66 times the ultimate load, in all the tested beams is well within the permissible serviceability limits (i.e., deflection less than Span/250) as per the existing Indian standard code of practice. Hence it can be considered that the use of WWM in place of conventional stirrups has not violated any serviceability criteria. Further there is an increase in the slope of shear crack with vertical (Table 4.1) in the RC beams provided with weld mesh as transverse reinforcement indicating the enhanced effectiveness of weld mesh compared to that of the conventional stirrups.

4.8.2 RC Beams with Core Zone Longitudinal reinforcement

During the testing the RC beam (R160) provided with conventional stirrups at 160mm spacing (i.e. spacing of stirrups equal to 0.6d) as transverse reinforcement has failed in shear at an ultimate load of 176.04 kN by developing a diagonal tension crack in shear span as expected (Fig 4.13(b)). This is because the beam R160 was intentionally designed to fail in shear by keeping the spacing of stirrups (160mm) larger than that required to avoid shear failure. However, when the RC beam L160 having the spacing of stirrups equal to that of R160 but in addition having the welded wire mesh by way of longitudinal core zone reinforcement, has failed at an ultimate load of 272.32 kN by developing clear flexural cracks (Fig.4.13(j)). Though the control beam was designed to fail in shear but the provision of longitudinal core zone reinforcement in the form of welded wire mesh made the RC beam L160 to fail in flexure. This indicates the effectiveness of longitudinal core zone reinforcement in transforming the failure from shear to flexure and increasing the ultimate load. The RC beams L180 and L200 wherein the spacing of stirrups is increased (0.68d and 0.75d respectively) by retaining the welded mesh as longitudinal core zone reinforcement have also failed in flexure at ultimate loads much higher than that of R160 but less than that of RC beam L160. Though the RC beams L160, L180 and L200 have developed shear cracks initially but these shear cracks were stopped extending further at about 70 to 80% of the ultimate load and allowed the flexural cracks near the middle of the span to grow and caused the crushing of concrete in the compression zone at ultimate. This clearly indicates the effectiveness of longitudinal core zone reinforcement in avoiding the shear failure and increasing the ultimate load. In the case RC beam (L265) provided with stirrups at spacing equal to the effective depth of the beam but provided in form of longitudinal core zone reinforcement has failed in shear similar to that of R160 beam wherein there was no longitudinal core zone reinforcement and the spacing of stirrups was 0.6d. However the ultimate load of the RC beam L265 was 181.55, which is about 3% higher than that of the RC beam R160. Also it was observed that there was delay in the appearance of first cracks in all the RC beams having longitudinal core zone reinforcement apart from conventional stirrups. Here the significant point to be noticed is that in the RC beams having the welded wire mesh by means of longitudinal core zone reinforcement, though there is decrease in the ultimate load with increase in the spacing of stirrups up to effective depth, but the least load observed (in RC beam L265) is more than that of R160 where there was no longitudinal core zone reinforcement.

The deflection at service load (taken as two thirds of ultimate, shown in Table 4.9) in all the three beams tested, is very much less than the allowable deflection (Span /250) as per the existing Indian code of practice for the design of RC members. This indicates the use of mesh as transverse reinforcement replacing conventional stirrups did not violate the required serviceability norms.

The total weight of steel consumed in using the welded wire mesh by means of longitudinal core zone reinforcement apart from stirrups is about 30% more than that consumed in using only conventional stirrups as transverse reinforcement. However, the ultimate (failure) load observed in L160 beam is about 54.7% more than that of R160 beam. The increase in the ultimate load may be attributed to the continuous resistance provided by the longitudinal core zone reinforcement in the form of welded wire mesh. Particularly the mesh provided longitudinally in the core zone provides resistance in continuous manner unlike the discrete resistance provided by the regular stirrups. The continuity in resistance provided by the prefabricated mesh against diagonal tension due to shear delays the formation of shear cracks and improves the performance of reinforced concrete members. Further the increase in the consumption of the steel in using additional reinforcement in the core zone in the form of welded wire mesh can be compensated by reducing the number of stirrups by adopting the higher spacing of stirrups than required. The behavior of the beams as described above indicatedthe superior performance of welded wire mesh by means of longitudinal core zone reinforcement over the performance of RC beam with conventional stirrups / mesh by way of core zone transverse reinforcement from the point of altering the failure from shear to flexure and simultaneously increasing the ultimate load. However, the performance of weld mesh as core zone longitudinal reinforcement need to be investigated for the shear span to depth ratios other than 3, adopted in the present investigation.

The provision of core zone reinforcement has shown not only increase in ultimate (failure) load but also changed the nature of failure from shear to flexure compared to that of the RC beams provided with only conventional stirrups. For the same spacing of stirrups as transverse reinforcement, the RC beam provided with weld mesh as longitudinal core zone reinforcement has shown not only increase in ultimate (failure) load but also changed the nature of failure from shear to flexure compared to that of the RC beams provided with only conventional stirrups.

Here the significant point to be noticed is that the provision of longitudinal core zone reinforcement in the form of welded wire mesh along with conventional stirrups has the following simultaneous benefits: i) Increase in ultimate load ii) Change in the mode of failure from brittle (shear) to ductile (flexure) and iii) formation of a greater number of smaller cracks. The increase in the ultimate load may be attributed to the continuous resistance provided by the longitudinal core zone reinforcement in the form of welded wire mesh. Particularly the mesh provided longitudinally in the core zone provides resistance in continuous manner unlike the discrete resistance provided by the regular stirrups. The continuity in resistance provided by the prefabricated mesh against diagonal tension due to shear delays the formation of shear cracks and improves the performance of Reinforced concrete members. On observing the behavior of RC beams with core zone reinforcement it is possible to use a smaller number of stirrups i.e by adopting higher spacing of stirrups that prescribed by the code of practice [IS 456. (2000)]. However, this aspect requires confirmation by going for further testing of RC beams with stirrups at different spacing's along with core zone reinforcement. Also, the performance of weld mesh as core zone longitudinal reinforcement need to be investigated for the shear span to depth ratios other than 3, adopted in the present investigation. The simplicity in the means of resisting shear in reinforced concrete members by using a welded wire mesh as longitudinal core reinforcement apart from conventional stirrups / ties may enable the fabricators of reinforcement cages in the rapid adoption of technology in the construction field.

4.9 Comparison of transverse and longitudinal Core zone reinforcement

For comparing the improvement in the load capacity due to transverse and longitudinal core zone reinforcement in the form of WWM, the RC beams having similar quantity of shear reinforcement (in the form of stirrups and /or WWM) were considered.

4.9.1 Transverse mesh as core zone reinforcement

Total weight of shear reinforcement and ultimate load capacity in R160 beam provided with 6mm stirrups at 160 mm c/c are 1.21 kg and 136.92 kN respectively.

Total weight of shear reinforcement and ultimate load capacity in M100 beam provided with WWM at 100mm are 0.88 kg and 181.66 kN respectively. In the case of M60 beam provided with WWM at 60 mm c/c, the total weight of shear reinforcement and ultimate load capacity are 1.43 kg and 206.14 kN respectively. Hence by linear interpolation, it can be obtained that the RC beam provided with WWM as core zone transverse reinforcement at 75mm c/c (may be designated as M75 beam) will be equivalent to R160 beam provided with 6mm stirrups at 160 mm from the point of total shear reinforcement. However, the ultimate load capacity of RC beam provided with WWM as a transverse reinforcement at 75mm c/c will be

196.92 kN (obtained by linear interpolation). This indicates that in the case of RC beams provided with WWM as a core zone transverse reinforcement will have 43% upgradation in the ultimate load capacity compared to the RC beam with conventional stirrups as a shear reinforcement. Further the significant point here is that for similar quantity of transverse reinforcement, the R160 beam has failed in shear whereas the M75 RC beam provided with WWM as shear reinforcement in the form of WWM fails in flexure. Thus with the use of WWM as transverse core zone reinforcement, there is a possibility change in the nature of failure from shear to flexure.

4.9.2 Longitudinal mesh as core zone reinforcement

Total weight of shear reinforcement and ultimate load capacity in R160 beam provided with 6mm stirrups at 160 mm c/c are 1.54 kg and 176.04 kN respectively.

Total weight of shear reinforcement and ultimate load capacity in L265 beam provided with WWM as a longitudinal core zone reinforcement apart from 6mm stirrups at 265mm c/c are 1.53 kg and 181.50 kN respectively. This indicates that in the case of RC beams provided with WWM as a core zone longitudinal reinforcement will have only 3.1% improvement in the ultimate load capacity compared to the RC beam with conventional stirrups as a shear reinforcement. Further there is no change in the nature of failure between R160 and L265 beams.

Hence it can be concluded that the WWM as a transverse core zone reinforcement is about 40% more effective compared to the WWM as longitudinal core zone reinforcement, in improving the ultimate load capacity.

4.10 Conclusions

The following are the conclusions arrived at after the study of the efficacy of the Welded Wire Mesh (WWM) used either by means of transverse reinforcement in the core zone replacing totally the use of conventional stirrups or as longitudinal reinforcement in the core zone apart from conventional rectangular stirrups, in improving the performance of RC beam in shear and these conclusions are valid for this group of beams with a/d ratio as 3

1. For the same spacing of stirrups as transverse reinforcement, the RC beam provided with weld wire mesh as longitudinal core zone reinforcement has shown not only increase in ultimate (failure) load but also changed the nature of failure from shear to flexure compared to that of the RC beams provided with only conventional stirrups.

2. The use of longitudinal core zone reinforcement provides shear resistance in continuous manner unlike the discrete resistance provided by the regular stirrups.
3. The continuity in resistance provided by the longitudinal core zone reinforcement against diagonal tension due to shear delays the formation of shear cracks and improves the performance of reinforced concrete members.
4. The increase in the consumption of the steel in using additional reinforcement in the form of welded wire mesh as a longitudinal core zone reinforcement can be compensatedby reducing the number of stirrups by adopting the higher spacing of stirrups than required used as longitudinal core zone reinforcement.
5. The use of welded wire mesh as a longitudinal core zone reinforcement along with reduced number of regular stirrups did not violate the required serviceability norms.
6. In the case of RC beam provided with longitudinal core zone reinforcement in place of conventional stirrups, enhanced the resistance at ultimate, similar to that of conventional stirrups
7. The RC beam with longitudinal core zone reinforcement apart from conventional stirrups has shown more number of smaller width cracks indicating enhanced ductility.
8. For the same spacing of transverse steel, the ultimate load of the RC beams with welded wire mesh as a transverse reinforcement is more compared to the RC beams with conventional stirrups.
9. For the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM will be able to provide similar or better performance of RC beams compared to that of RC beams having conventional stirrups.
10. The nature of failure / behavior of the RC beam remained more or less similar with the replacement of conventional stirrups with welded wire mesh as transverse core zone reinforcement for the same spacing of transverse steel in the form of mesh / stirrups.
11. As the spacing of transverse reinforcement (in the form of mesh / stirrups) reduced, the rate of increase of load in beams with weld mesh as core zone transverse reinforcement is observed to be more than that of beams with conventional stirrups
12. The increase in the ultimate loads together with satisfactory serviceability behavior and reduced consumption of transverse steel justifies the effectiveness of welded wire mesh as a transverse core zone reinforcement over the conventional stirrups.
13. For the same spacing of transverse reinforcement (in the form of mesh / stirrups) the weight of steel consumed in using the mesh as transverse core zone reinforcement is almost half of the weight of steel consumed in conventional stirrups for the same spacing leading to the economy in the steel quantity.

14. The use of mesh either as transverse core zone reinforcement substituting the conventional stirrups or as longitudinal core zone reinforcement did not violate the required serviceability norms.
15. The behavior of the RC beams tested clearly indicates the superiority of the welded wire mesh either as transverse reinforcement replacing the conventional stirrups or as longitudinal core zone reinforcement from the point of performance at ultimate.
16. The welded wire mesh as a transverse core zone reinforcement is about 40% more effective compared to the welded wire mesh as longitudinal core zone reinforcement, in improving the ultimate load capacity.

Chapter 5

A STUDY ON THE EFFECT OF WELDED WIRE MESH AS A CORE ZONE TRANSVERSE REINFORCEMENT

Chapter 5

A STUDY ON THE EFFECT OF WELDED WIRE MESH AS A CORE ZONE TRANSVERSE REINFORCEMENT

5.1. General

In the first phase of investigation, it was concluded that the use of WWM as a core zone reinforcement replacing totally the conventional stirrups is effective enhancing the shear performance of RC beams. The investigation was conducted only on a single type of WWM. Hence in this phase of investigation, the experimental investigation was carried out by considering different types of WWM i.e., the Welded wire meshes having different spacing's and diameter of the wires. The main objective in the present investigation is to study and quantify the performance of RC beams wherein the welded wire mesh is used in the core zone as transverse reinforcement and compare the same with the shear performance of RC beams provided with conventional stirrups are presented in fig 5.1 and 5.2

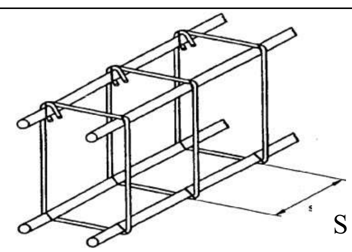


Fig.5.1 Conventional Stirrups as transverse reinforcement

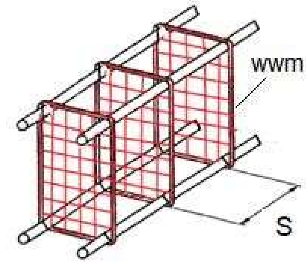


Fig.5.2 WWM as transverse reinforcement in place of regular stirrups

5.2. Experimental program

The experimental study involves casting and testing of seventeen number of RC beams having shear span to depth ratio of three. In this experimental program, few beams are intentionally designed to fail under shear and remaining beams are designed to fail under flexure. Out of seventeen beams, one beam has no transverse reinforcement near the supports, but the middle 500mm length of the beam has two legged 6mm diameter stirrups at a spacing of 100 mm c/c and is designated as 'C100'. The purpose of testing 'C100' beam is to know the shear strength of RC beam without any transverse reinforcement near the supports i.e., in the maximum shear zone under four-point bending. Remaining sixteen beams are divided into four sets consisting of four beams in each set. Each set of RC beams represent a different spacing of shear reinforcement adopted. The spacings of transverse reinforcement (S) adopted are 85, 125, 170 and 215mm, representing the transverse spacing ratios (S/d) of 0.38, 0.56, 0.76 and 0.96

respectively. The beams are designed for required spacing of 170mm and beams with spacing's of 85mm,125mm are intentionally designed to fail under flexure and spacing of 170mm and 215mm are designed to fail under shear. The spacing 215mm is selected as near to effective depth such that the enhanced shear property of beams with meshes will be assessed till maximum extent. Out of four numbers of RC beams in each set, one beam has shear reinforcement in the arrangement of regular stirrups and is designated with letter 'R'. The remaining three beams are provided with WWM as transverse core zone reinforcement substituting the conventional stirrups. However, the spacing of transverse reinforcement (stirrups or WWM) is kept constant in each set of four beams. In this investigation, three dissimilar types of Welded wire mesh were used and they are designated as 1M, 2M and 3M respectively. The details of diameter, spacing of wires in each of these WWM are given in Table 5.1. The flexural steel reinforcement adopted was retained constant in all the seventeen RC beams tested. Thus, the RC beam specimen whose designation is R125 stands for RC beam provided with regular stirrup as transverse (shear) reinforcement at a spacing of 125mm c/c. The RC beam specimen whose designation is 2M125 stands for RC beam provided with 2M type welded wire mesh as transverse (shear) reinforcement at a spacing of 125mm c/c.

Table 5.1 : Welded wire Mesh Parameters used as Transverse Reinforcement

Type of WWM	**1M**	**2M**	**3M**
No.of Vertical bars (Nv)	3	5	3
No. of horizontal bars (Nh)	5	4	5
Dia of Vertical bars (φv) in mm	2.40	2.50	2.56
c/s Area of Vertical bars (Av) in sq.mm	4.52	4.91	5.14
Dia of Horizontal bars (φh) in mm	2.4	3.74	2.6
c/s Area of Horizontal bar (Av) in sq.mm	4.52	10.98	5.31
Spacing of Vertical bars (Sv) in mm	45	25	45
Spacing of Horizontal bars (Sh) in mm	45	70	50
Yield strength (MPa)	345	326	338
Ultimate strength (MPa)	462	422	428
Average weight of each mesh (kg)	0.043	0.081	0.050
% weight of the WWM compared to the weight of stirrup	-35.5	-66.9	-41.3
Weld mesh factor (Wmf) = [(NvAv + Nh Ah) / Nv Av] x (bd/Sv Sh)	45.92	55.61	42.15

.

The details of specimens tested and compressive strength along with beam dimension details are given in Table.5.2

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Table.5.2 Details of RC Beam specimens tested of Phase-II beams				
SNo	**Beam**	**Transverse Reinforcement**	**Details of the Beam**	
1.	C100	No stirrups in the Shear zone	**Shear span to depth ratio - 3** **Size of RC Beam -** 155 x 255 x 1700 mm Effective depth (d) = 225 mm Shear span(a)= 675 mm Effective Span (L) = 1550 mm Overall length = 1700 mm **Concrete** Compression Strength= 31.4 MPa **Effective c/s Area of RC Beam** bd = 155 x 225 = 34875 sq.mm	**Longitudinal Reinforcement** (Maintained constant in all the beams) 2-16mm dia and 1-10mm dia Yield Strength = 424 MPa Ultimate Strength = 538 MPa **Stirrup (R)** Diameter of Stirrup bar = 5.5mm c/s Area of Stirrup bar = 23.75 sq.mm Yield Strength = 292 MPa Ultimate Strength= 389 MPa Average weight of each stirrup = 0.121 kg
2.	R85	2 Lgd Stirrup @85 c/c		
3.	1M85	1M-WWM @ 85 c/c		
4.	2M85	2M-WWM @ 85 c/c		
5.	3M85	3M-WWM @ 85 c/c		
6.	R125	2 Lgd Stirrup @ 125 c/c		
7.	1M125	1M-WWM @ 125 c/c		
8.	2M125	2M-WWM @ 125 c/c		
9.	3M125	3M-WWM @ 125 c/c		
10.	R170	2 Lgd Stirrup @ 170 c/c		
11.	1M170	1M-WWM @ 170 c/c		
12.	2M170	2M-WWM @ 170 c/c		
13.	3M170	3M-WWM @ 170 c/c		
14.	R215	2 Lgd Stirrup @ 215 c/c		
15.	1M215	1M-WWM @ 215 c/c		
16.	2M215	2M-WWM @ 215 c/c		
17.	3M215	3M-WWM @ 215 c/c		

The typical WWM of different meshes and its reinforcement cages used are shown in Fig. 5.3

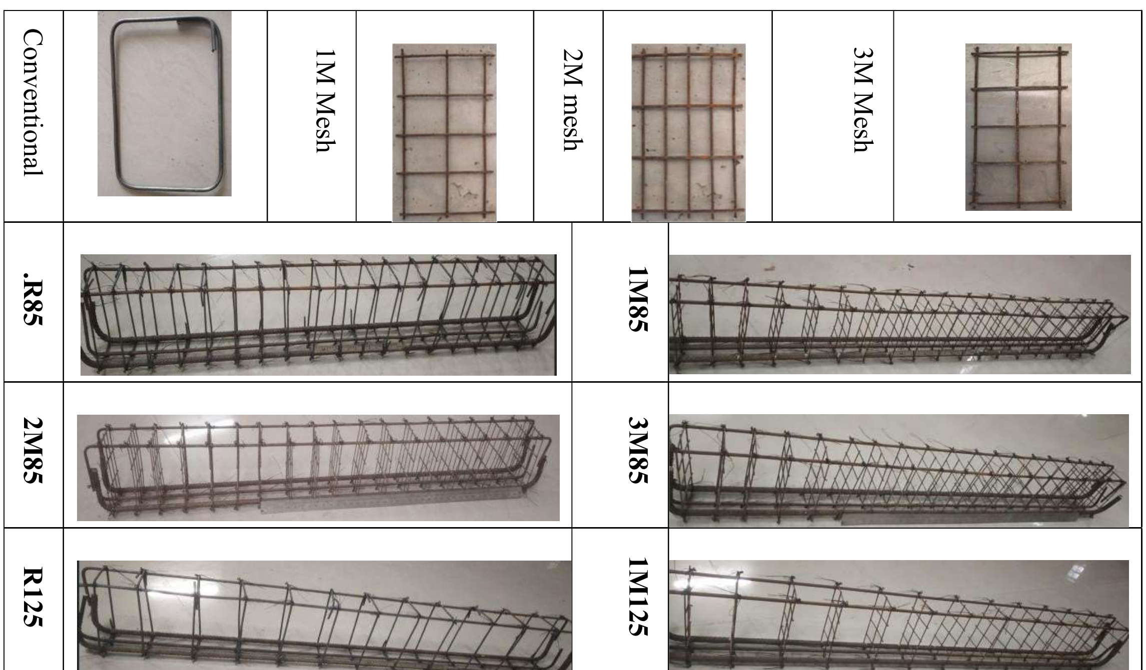


Fig 5.3 Details of 1M, 2M and 3M meshes and reinforcement cages used in RC beams

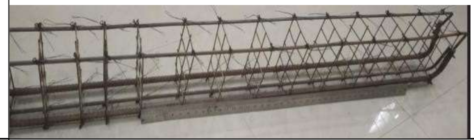
2M125		3M125	
R170		1M170	
2M170		3M170	
R215		1M215	
2M215		3M215	
C100			

Fig 5.3 Details of 1M, 2M and 3M meshes and reinforcement cages used in RC beams

5.3. Concrete mix proportion used

The materials used consist of Ordinary Portland Cement(OPC) 53 grade cement confirming to IS 269-2015, the fine aggregate conforming to zone-II of IS: 383 (2016), the 20mm nominal size coarse aggregate, the potable water and super plasticizer. The bulk density and specific gravity and of fine aggregate are 1.45 g/cm^3 and 2.65 respectively and that of coarse aggregate are 1.5g/cm^3 and 2.80 respectively. The M25 grade concrete was used and the details of concrete mix proportion are as follows:

Mix proportion: 1: 1.9: 3.3 w/c 0.47	Cement: 360 Kg	Super plasticizer: 2.7 kg

5.4. Casting and testing of beams

For casting the RC beams the steel channel moulds of required size were used. After placing the prefabricated steel reinforcement cages the concreting was done with proper compaction. A day after casting, the beam samples were de-moulded carefully and water cured at an average room temperature and relative humidity of 35±2ºC and 75% are respectively.

After the completion of 28 days of water curing, the specimens were dispatched from the curing pond and kept under the shade separately. The beams were tested under two-point loading (four-point bend test) maintaining the required shear span to depth ratio. The TINIUS – OLSEN testing machine of capacity 2000kN was used for testing the beam specimens. The LVDTs and the dial gauges were used to measure the deflections during the testing. The test setup details were shown in Fig.5.4 and its schematic diagram represented in Fig 5.5

Fig 5.4 Test Setup details

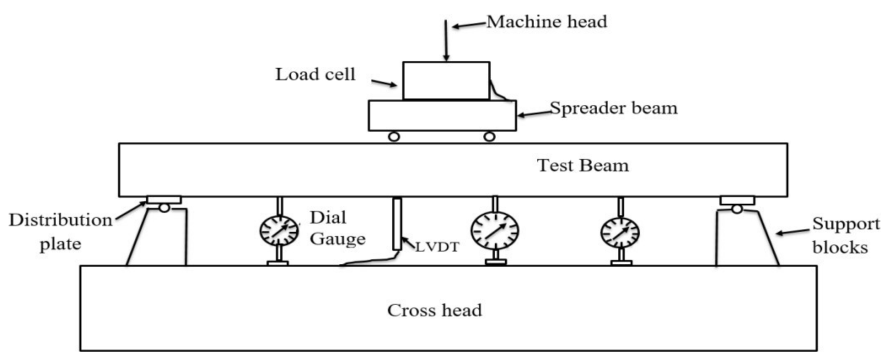


Fig 5.5 Schematic Representation of Test setup

The displacement control equal to 1/1500 of Span per minute was adopted for testing the beam specimens (JSCE SF4, 1985). The testing was continued till the point of ultimate load or the test set up reaches to unstable, whichever is earlier.

The Table 5.3 gives the experimentally obtained ultimate loads and maximum recorded deflections.

Table 5.3 Experimentally recorded loads and deflections of Phase-II							
S. No	**Beam**	**S/d**	**At Service**		**At Ultimate**		**Nature of failure At Ultimate**
			Ps (kN)	**ds (mm)**	**Pu (kN)**	**du (mm)**	
1.	C100	--	56.9	1.7	85.4	4.6	Shear
2.	R85	0.38	86.4	3.6	149.6	15.9	Flexure
3.	1M85	0.38	85.2	4.4	137.82	16.8	Flexure-shear
4.	2M85	0.38	101.7	3.5	167.6	23.3	Flexure
5.	3M85	0.38	83.9	2.9	145.5	16.2	Flexure
6.	R125	0.56	74.9	3.2	126.5	8.35	Flexure
7.	1M125	0.56	72.3	2.5	118.22	20.9	Flexure-shear
8.	2M125	0.56	83.8	3.9	143.9	20.7	Flexure
9.	3M125	0.56	75.2	3.2	127.8	17.5	Flexure
10.	R170	0.76	69.1	2.6	118.1	8.44	Shear
11.	1M170	0.76	66.5	3.1	105.2	10.2	Shear
12.	2M170	0.76	75.4	2.1	127.5	14.3	Flexure
13.	3M170	0.76	69.2	2.3	108.8	15.8	Flexure-shear
14.	R215	0.96	65.4	3.6	106.3	8.7	Shear
15.	1M215	0.96	64.5	2.3	100.6	12.3	Flexure-shear
16.	2M215	0.96	70.2	2.4	115.5	15.3	Flexure-shear
17.	3M215	0.96	65.1	2.3	103.2	15.9	Flexure-shear

The crack patterns and nature of failures are clearly presented in fig 5.6.

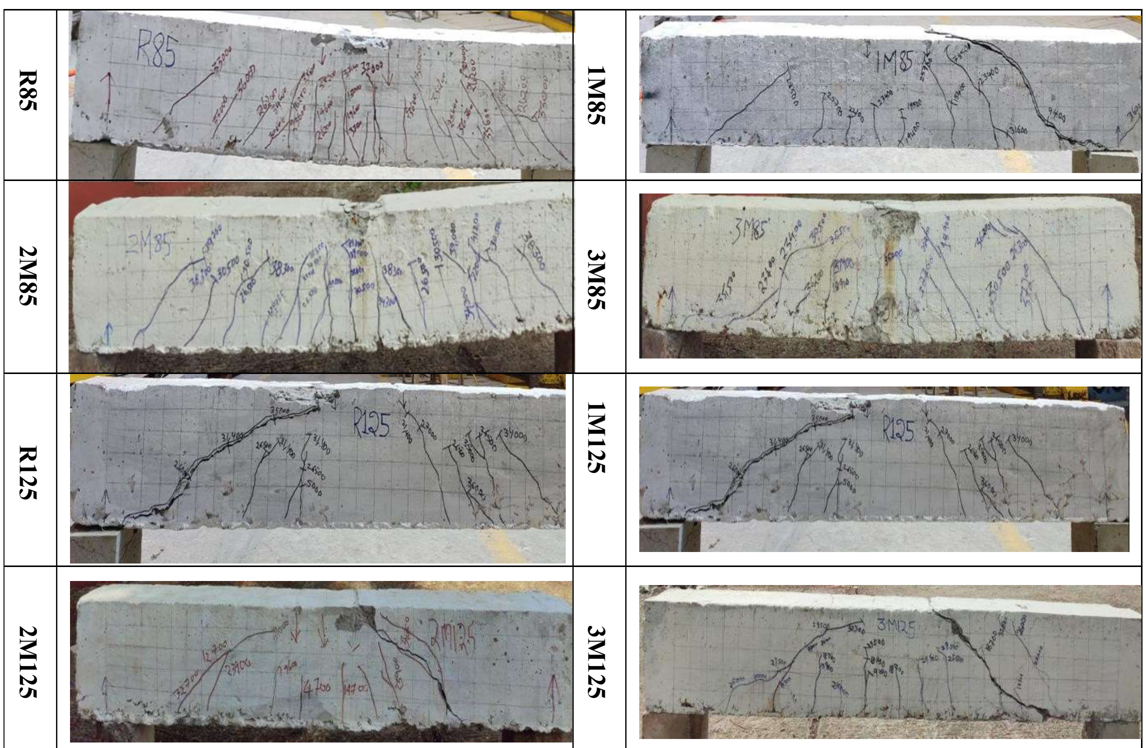


Fig 5.6 Failure pattern of RC Beams

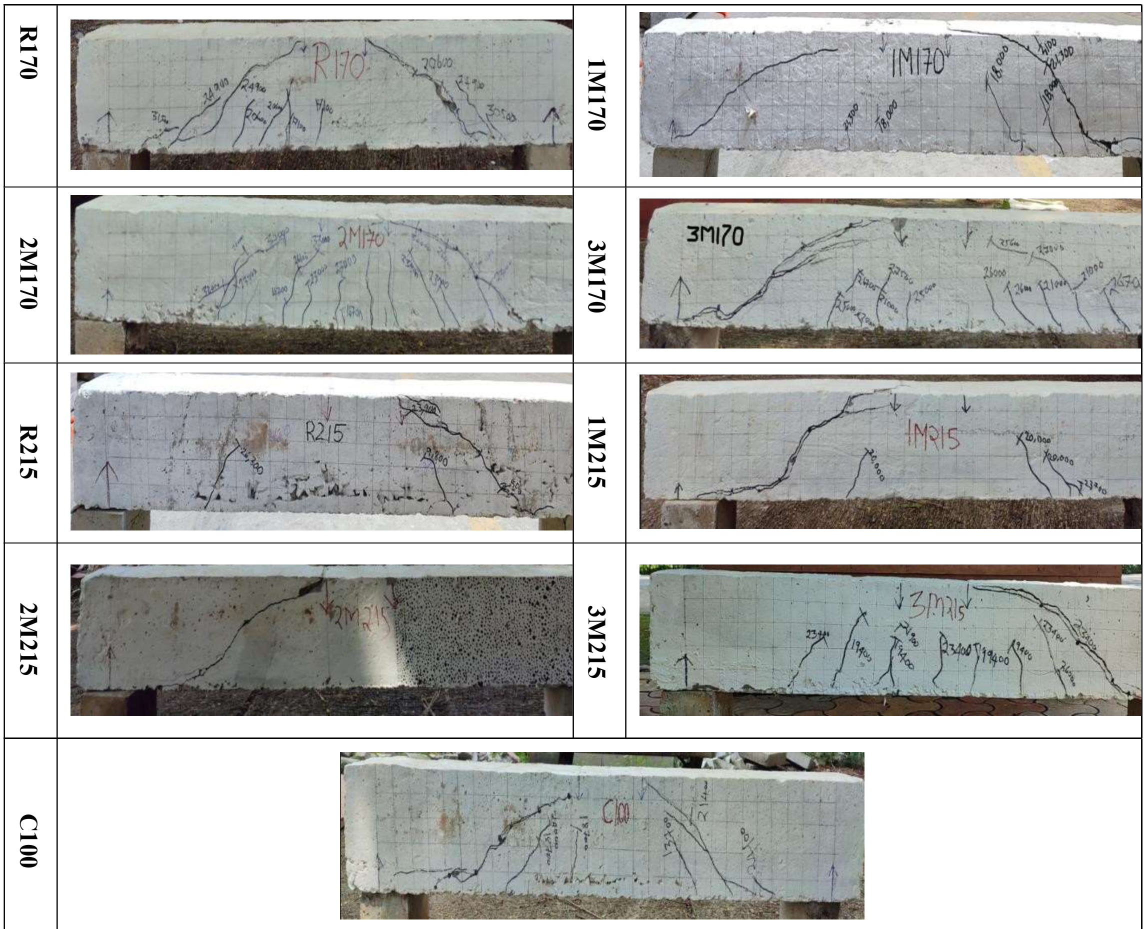


Fig 5.6 Failure pattern of RC Beams

5.5. Discussion of behavior and analysis of test results

5.5.1. Behavior of RC beams

The observations made during the testing indicated that the increase in the spacing of transverse reinforcement has in general reduced the ultimate loads. In most of the beams the first crack formed was a flexural crack in the uniform moment zone (i.e., between the loading points). The increase in the load caused the adequate progress of inclined (shear) cracks that propagated near the loading points. The shear strength observed in beams with stirrups as transverse reinforcement is 64.8 kN, 56.2 kN, 51.7 kN and 49.1 for S/d equal to 0.38, 0.56, 0.76 and 0.96 respectively. However, the average shear strength observed in beams with WWM as transverse reinforcement is 67.7 kN, 57.8 kN, 52.8 kN and 49.9 kN for S/d equal to 0.38, 0.56, 0.76 and 0.96 respectively. This indicates that for the similar spacing's of the shear reinforcement, the average shear strengths of the beams provided with WWM as transverse reinforcement have always either equal to or more than the shear strengths recorded in beams with stirrups as transverse reinforcement. This occurred even though the weight of the WWM compared to the weight of stirrup is less and therefore indicate the effectiveness of WWM over the stirrups for the similar spacing's of the transverse reinforcements. This may be attributed to the better crack control / delay of the diagonal cracks due to the existence of core zone reinforcement in the form WWM. For RC beams wherein, the shear strength is governed by the beam action which include the truss mechanism apart from interlocking of aggregates and dowel action, the vertical transverse reinforcement either in the form of stirrups or WWM is able to provide better shear resistance. This indicates clearly the economy and effectiveness ofWWM over the conventional stirrups. Further it is noticed that there is no shift in the nature / behavior of the RC beam with the replacement of regular stirrups with WWM as shear reinforcement for the similar spacing of transverse steel in the form of mesh / stirrups.

The observation of the deflections in which load at service i.e at 0.66 times the ultimate load, in all the tested beams is well within the permissible serviceability limits as per IS 456 i.e the deflections are less than Span / 250. Hence it can be concluded that the use of WWM in place of conventional stirrups has not violated any serviceability criteria.

5.5.2. Analysis of test results

The results of the experimental investigation presented above has showed that even the less quantity of transverse steel in the form of welded wire mesh, which distribute uniformly across the central zone of the transverse section of RC beam performed better than conventional two-legged stirrups in enhancing the shear strength. Hence in order to quantify the effect of welded wire mesh by means of transverse reinforcement in enhancing the shear resistance of RC beams a simple and new parameter termed as **'Mesh Index'** has been proposed and quantified. The Mesh index (Km) proposed takes in to account considering the effect of the presence of horizontal wires (i.e., the wires of the weld mesh parallel to the width of the RC beam) welded to the vertical wires in WWM in providing the shear resistance of RC beam having WWM as transverse reinforcement substituting conventional stirrups. The mesh index proposed considers three parameters related to the shear reinforcement in the form of mesh / stirrups i.e., 1) Area ratio 2) Distribution density and 3) Spacing ratio, which are defined as stated below are presented in Table 5.4

Table 5.4 Representation of mesh index parameters of phase-II			
1.	Area ratio	=	Ratio of total cross-sectional area of both vertical and horizontal bars to the cross-sectional area to vertical legs of transverse steel (stirrup or mesh) = [(NvAv + Nh Ah) / Nv Av]
2	Distribution density	=	Distribution of transverse steel across the cross-section i.e., Number of apertures = bd/ (Sv Sh)
3.	Spacing ratio	=	Spacing of transverse steel to the effective depth = S/d

The product of area ratio and distribution density is termed as the Weld mesh factor (Wmf) and is given for each type of mesh in the Table 5.1. The mesh index proposed can be written as:

$$\text{Mesh Index (Mi)} = \frac{\text{Weld mesh factor}}{\text{Spacing ratio}} = \frac{[(\text{NvAv} + \text{Nh Ah}) / \text{Nv Av}]\ (\text{bd}/\text{Sv Sh})}{\text{S}/\text{d}}$$

A simplified analysis has been carried out based on the principles of truss analogy for shear which is adopted by most of the structural concrete design codes. As per the truss analogy, the web bars are assumed to act as tension members of an imaginary truss and the compression in the concrete constitute the strut members. In RC beams, the shear resistance is given by the sum of the concrete shear resistance and the web steel resistance. Thus, following the truss analogy, the shear resistance of the RC beam provided with web reinforcement (either in the form of conventional stirrups or WWM) can be written as

$$Vu = Vc + Vs,$$

Where Vc = Concrete shear resistance offered without any web reinforcement (taken from the shear strength of C100 beam)

Vs = Shear resistance offered by the web steel in the form of stirrups or WWM

= K fy (NvAv) d / S,

where fy = Yield strength of stirrup or mesh wires in vertical direction,

NvAv = Cross sectional area of all vertical bars of the Stirrup or the WWM,

S = spacing of the transverse reinforcement in the form of stirrups or WWM along the length of the beam.

K= A factor accounting for the effect transverse reinforcement in the form of stirrups or WWM.

Hence, Vs = Vu – Vc = (K fy Av d / S). On simplifying, K = [(Vu-Vc) S/d] / fy Av

From the experimental results the value of K has been evaluated for different mesh index (Mi) and are given in Table 5.5.

The variation of K factor with Mesh index is shown in Fig.5.7 for all the beams. It is observed from the Fig.5.7, that there exists a good correlation of K factor values with mesh index. The best fit equation relating the K factor and mesh index proposed is:

$$\mathbf{K = 0.539\ (Mi)^{0.287} \quad R^2 = 0.916}$$

Using the above proposed K factor, shear strength has been calculated as follows and are tabulated in Table 5.5.

$$\mathbf{Vu = Vc + Vs = Vc + (K\ fy\ NvAv\ d / S)}$$

The relationship between experimental and calculated shear strengths is 0.983. Hence mesh index criteria can be used to estimate the shear strength of RC beams provided with transverse reinforcement either in the form of stirrups / WWM.

Table 5.5 K factor for different Mesh index of Phase-II beams													
SNo	**Beam**	**S/d**	**Mi**	**Pu, exp (kN)**	**Vu (kN)**	**Vu – Vc (kN)**	**fy (MPa)**	**NvAv (mm^2)**	**fyNvAv (kN)**	**K**	**Pu,cal**	**Vu,cal**	**Vu,expt / Vu,cal**
1.	R85	0.38	7.51	149.6	74.80	32.10	292	47.49	13.87	0.874	155.97	77.99	0.96
2.	1M85	0.38	121.57	137.82	68.91	26.21	345	13.56	4.68	2.116	138.36	69.18	1.00
3.	2M85	0.38	147.20	167.6	83.80	41.10	326	24.53	8.00	1.942	181.01	90.51	0.93
4.	3M85	0.38	111.57	145.5	72.75	30.05	338	15.43	5.22	2.176	143.00	71.50	1.02
5.	R125	0.56	5.10	126.5	63.25	20.55	292	47.49	13.87	0.823	128.36	64.18	0.99
6.	1M125	0.56	82.67	118.22	59.11	16.41	345	13.56	4.68	1.948	117.64	58.82	1.00
7.	2M125	0.56	100.10	143.9	71.95	29.25	326	24.53	8.00	2.032	143.60	71.80	1.00
8.	3M125	0.56	75.86	127.8	63.90	21.20	338	15.43	5.22	2.258	120.46	60.23	1.06
9.	R170	0.76	3.75	118.1	59.05	16.35	292	47.49	13.87	0.891	114.32	57.16	1.03
10.	1M170	0.76	60.78	105.2	52.60	9.90	345	13.56	4.68	1.598	107.10	53.55	0.98
11.	2M170	0.76	73.60	127.5	63.75	21.05	326	24.53	8.00	1.989	124.58	62.29	1.02
12.	3M170	0.76	55.78	108.8	54.40	11.70	338	15.43	5.22	1.695	109.00	54.50	1.00
13.	R215	0.96	2.97	106.3	53.15	10.45	292	47.49	13.87	0.720	106.78	53.39	1.00
14.	1M215	0.96	48.06	100.6	50.30	7.60	345	13.56	4.68	1.552	101.44	50.72	0.99
15.	2M215	0.96	58.20	115.5	57.75	15.05	326	24.53	8.00	1.798	114.36	57.18	1.01
16.	3M215	0.96	44.11	103.2	51.60	8.90	338	15.43	5.22	1.630	102.85	51.42	1.00
Note: Vu = Shear force = Pu, exp/2 Vc = 85.4/2 = 42.7 kN K = [(Vu-Vc) S/d] / fy Av								Correl. between Vu expt and Vu,cal = 0.983					

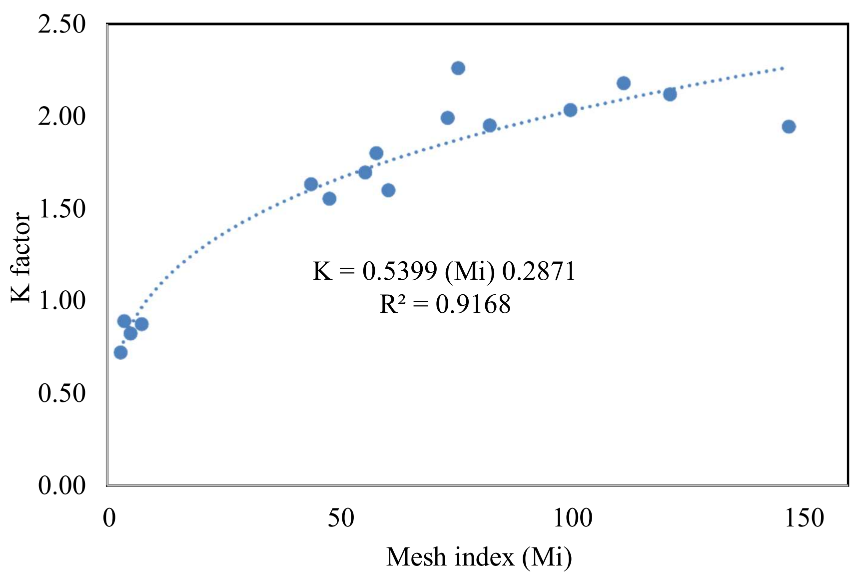


Fig.5.7 Variation of K factor with Mesh index of phase-II

5.5.3. Effect of the ratio of the c/s area of vertical legs of WWM to stirrups

In order to quantify the minimum required cross-sectional area of the vertical wires of the WWM, the following analysis is carried out. Fig.5.8 shows the variation in the ratio of shear strength due to WWM to the stirrups (Vum/Vus) with the ratio of c/s area of vertical legs of WWM to that of stirrups (Avm/ Avs).

Where,

Vum = (Vu-Vc) of the RC beam with WWM,

Vus = (Vu-Vc) of the RC beam with stirrups.

Avm = (NvAv) of the RC beam with WWM i.e., the cross-sectional area of all the vertical wires of the WWM used as transverse reinforcement.

Avs = (NvAv) of the RC beam with stirrups i.e., the cross-sectional area of the vertical legs of the conventional two-legged stirrup.

Hence Avm/Avs =[(NvAv) of wwm] /[(NvAv) of stirrup]

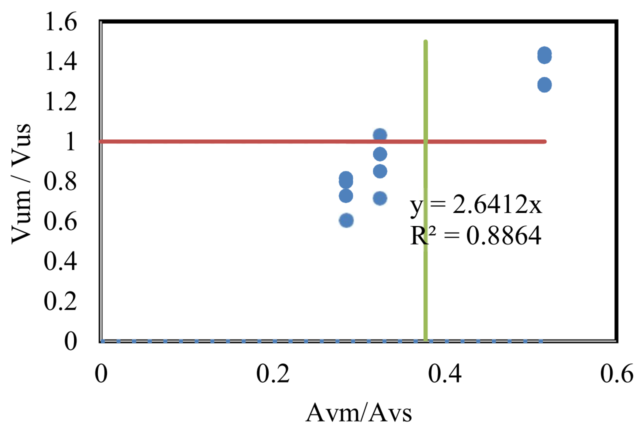


Fig.5.8 Effect of the Ratio of the c/s area of Vertical legs of WWM to stirrupson the ratio of Shear strength of Mesh to Stirrups

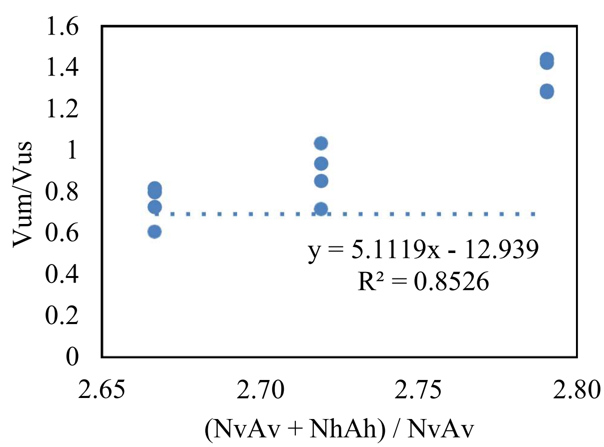


Fig.5.9 Effect of the Area Ratio of WWM on the ratio of Shear strength of Mesh to Stirrups

It is noticed from the Fig.5.8 that the beneficial effect of WWM from the point enhancement in the shear strength can be achieved only when the c/s area of vertical wires of WWM exceeds at least 37.8% i.e., 1/2.64 of the c/s area of the vertical legs of the conventional two-legged stirrup. However, taking the minimum values of Vum/Vus, observed, the minimum required Avm/Avs to have the beneficial effect of WWM over the stirrups from the point enhancement in the shear strength, will become 42.1%. The effect of area ratio of WWM i.e., the ratio of total cross-sectional area of both vertical and horizontal bars to the cross-sectional area of only vertical bars of transverse steel (stirrup or mesh) (NvAv + Nh Ah) / Nv Av) shown in Fig.5.9 indicates that a minimum area ratio of 2.72 is required to have the beneficial effect of WWM from the point enhancement in the shear strength over stirrups.

5.6. Validation of mesh index

The validation of the proposed mesh index is carried out by considering the chapter 4 data on the shear strength of RC beams provided with WWM as transverse reinforcement. From the published literature the details of the RC beams provided with WWM as shear reinforcement are collected and given in Table 5.6. A comparison is made between the K factor values obtained from the experimental ultimate loads and the K factor values corresponding to the mesh index calculated using the proposed equation is made and are given in Table 5.6 and alsoshown in Fig 5.10. The correlation between K_{expt}. and K_{cal}. is 0.911. Further the comparison of the experimental shear strengths is made with the calculated shear strengths and the results are given in Table 5.6 and also shown in Fig.5.11. The correlation between experimental (Vu expt) and calculated shear strength (Vu,cal) is 0.847.

The above discussion has clearly shown the superiority of WWM over the conventional stirrups for the similar transverse reinforcement spacing's from the point shear resistance and economy in RC beams. However, the effect of mesh index in estimating the shear strength of RC beams provided with WWM as a transverse core zone reinforcement needs to be further investigated for strength of concrete, percent of longitudinal steel and shear span to depth ratio other than those adopted in the present investigation and particularly for shear span to depth ratios less than 2.5

Table.5.6 Comparison of Experimental and Calculated Shear strengths

S.No	Beam	Transverse reinforcement	S/d	Mi	Pu,expt (kN)	Vu,expt (kN)	K	K,cal *	Vu,cal**
1.	R160	2 Lgd Stirrup @160 c/c	0.73	3.62	136.92	68.46	0.612	0.780	71.15
2.	R100	2 Lgd Stirrup @100 c/c	0.45	5.79	161.5	80.75	0.861	0.892	81.55
3.	R60	2 Lgd Stirrup @60 c/c	0.27	9.65	170.5	85.25	0.622	1.033	102.87
4.	M160	WWM @ 160 c/c	0.73	56.47	138.85	69.43	1.364	1.715	72.21
5.	M100	WWM @ 100 c/c	0.45	90.35	181.55	90.78	2.537	1.963	83.50
6.	M60	WWM @ 60 c/c	0.27	150.58	206.14	103.07	2.104	2.273	106.63
7.	C100	No stirrups	-	-	117.25		-	-	-

Correlation between K and K,cal = 0.911

Correlation between Vu,expt and Vu,cal = 0.847

*** K,cal = 0.539 (Mi) $^{0.287}$ (Prop equation)**

****Pu,cal = 2(Vc + K fy NvAv d / S)**

Vc = 117.25 /2 = 58.62 kN

Details of RC Beam specimens tested [7]

Shear span to depth – 3

Concrete
Compression Strength= 31.8 MPa

Effect. c/s Area of RC Beam
bd = 140 x 220 = 30800 mm^2

Size of RC Beam-
140 x 240 x 1650 mm
Effective depth (d) = 220 mm
Shear span(a)= 660 mm
Effective Span (L) = 1520 mm
Overall length = 1650 mm

Longitudinal Reinforcement
(Maintained constant in all the beams)
2-12mm dia and 1-16 mm dia
Yield Strength = 424 MPa
Ultimate Strength = 538 MPa

Stirrup (R)
Dia. of Stirrup bar = 5.1 mm
c/s area of Stirrup = 20.42 mm^2
Yield Strength = 285.6 MPa
Ultimate Strength= 361 MPa
Average weight of each stirrup = 0.12 kg

Details of Welded Wire Mesh (WWM)

Type of WWM	**M**
No.of Vertical bars (Nv)	5
No. of horizontal bars (Nh)	5
Dia of Vertical bars (φv) in mm	2.34
c/s Area of Vertical bars (Av) in sq.mm	4.30
Dia of Horizontal bars (φh) in mm	2.34
c/s Area of Horizontal bar (Av) in sq.mm	4.30
Spacing of Vertical bars (Sv) in mm	30
Spacing of Horizontal bars (Sh) in mm	50
Yield strength (MPa)	267.7
Ultimate strength (MPa)	347
Average weight of each mesh (kg)	0.055
% weight of the WWM compared to the weight of stirrup	-45.8
Weld mesh factor (Wmf) = [(NvAv + Nh Ah) / Nv Av] x (bd/Sv Sh)	41.06

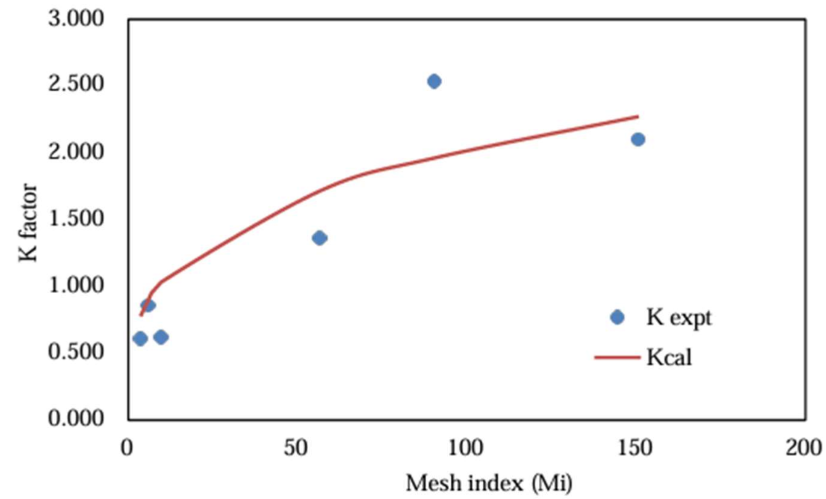


Fig.5.10 Comparison of K expt and K cal with Mesh index

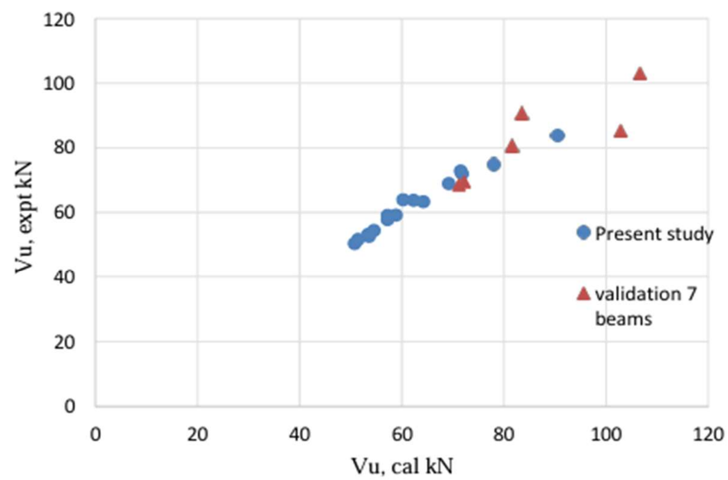


Fig 5.11 Comparison of Experimental and calculated shear strengths

5.7. Conclusions

The following conclusions were arrived from the study of WWM as core zone transverse reinforcement replacing the regular stirrups in RC beams.

1) The pattern of failure between the RC beams provided with WWM as a core zone transverse reinforcement and the RC beams provided with regular stirrups for the similar spacing of transverse steel is more or less similar.
2) For the similar spacing of transverse reinforcement, the quantity of transverse steel in the form of welded wire mesh of about 42 % of the stirrup area, is able to provide similar

or better shear load capacity of RC beams compared to that of RC beams having conventional stirrups.

3) In RC beams provided with WWM as a core zone transverse reinforcement, the new parameter termed as ‘Mesh index’, which takes in to account the area ratio, distribution density and spacing ratio, can be used in estimating the shear strengths.
4) A factor ‘K’ accounting for the effect transverse core zone reinforcement in the form of WWM or stirrups can be related to the ‘Mesh index (Mi)’ using:

$$\mathbf{K = 0.539\,(Mi)^{0.287}}$$

5) A minimum area ratio of about 2.72 is required to have the beneficial effect of WWM over stirrups from the point enhancement in the shear strength.
6) The acceptable performance at service together with less consumption of transverse steel justifies the use of welded wire mesh over the conventional stirrups as transverse reinforcement for the similar spacing of transverse steel.

Chapter 6

A STUDY ON THE EFFECT OF WWM AS A CORE ZONE TRANSVERSE REINFORCEMENT ON THE BEHAVIOR OF RC BEAMS WITH DIFFERENT SHEAR SPAN TO DEPTH RATIO

Chapter 6

A STUDY ON THE EFFECT OF WWM AS A CORE ZONE TRANSVERSE REINFORCEMENT ON THE BEHAVIOR OF RC BEAMS WITH DIFFERENT SHEAR SPAN TO DEPTH RATIO

6.1. General

In the second phase of investigation, the effect of using WWM as a core zone transverse reinforcement replacing totally the conventional stirrups, was quantified in terms of a new parameter 'Mesh index'. The investigation was conducted on RC beams with shear span to depth ratio of 3. The models based on flexure-shear interaction classifies the RC beams on the basis of shear span to depth ratio such as deep beams (a/d < 2.5) wherein the arch action is predominant and shallow beams (a/d >2.5) wherein the beam action is predominant [Slowik, (2014), Gunawan et al. (2020)]. ASCE-ACI Committee 445 indicated different types of RC beams based on a/d ratio viz: deep beams (a/d<1.0, Short beams (1 < a/d < 2.5) and ordinary shallow beams (a/d >2.5) (ASCE-ACI, 1998). The classification of RC beams based on Kani's valley indicates a/d =2.31 as a critical shear span to depth ratio because it discriminates between two failure modes: For a/d > 2.31, the beam mechanism governs and the failure is known as diagonal tension failure; for a/d < 2.31, the arch mechanism governs and the failure is usually termed as a shear-compression failure. Hence in this phase of investigation, the experimental investigation was carried out to study the effectiveness of WWM as a transverse reinforcement in RC beams having different shear span to depth ratios (a/d). The shear span to depth ratios selected are 2.2, 3 and 3.8 representing both arch action (a/d < 2.5) and beam action (a/d >2.5).

6.2. Experimental program

The experimental program involves casting and testing of twenty-four numbers of RC beams with three varying shear-span to depth ratios i.e., a/d =2.2, 3 and 3.8, represented by the letter A, B and C respectively. For each a/d ratio, eight numbers of RC beams were tested under symmetrical two-point loading (i.e Four-point bend test). The eight RC beams tested for each a/d ratio are divided in to two sets having four beams in each set. Thus, there are total six sets of RC beams were tested. Each set of RC beams represent a different spacing of shear reinforcement adopted. The beams with stirrups as of transverse reinforcement are intentionally designed to fail in shear following the standard truss analogy of shear in RC and accordingly, the spacing's of transverse reinforcement are adopted. For each a/d ratio two different spacing of transverse reinforcement are adopted i.e., 85mm, 135mm for a/d=2.2, 150mm, 235mm for a/d=3 and 240mm, 300 mm for a/d=3.8. Out of four numbers of RC beams in each set, one beam has shear reinforcement in the form of conventional stirrups and is designated with letter'R'. The remaining three beams are provided with WWM as shear reinforcement replacing the conventional stirrups. However, the spacing of transverse reinforcement (stirrups or WWM) is kept constant in each set of four beams. Three different types of WWM (1M, 2M and 3M) are used as transverse reinforcement in the experimental study. The longitudinal steel adopted was maintained constant in all the twenty-four RC beams tested. Thus, the RC beam specimen whose designation is A-R85 stands for RC beam with shear span to depth ratio of 2.2 and provided with conventional stirrup as transverse (shear) reinforcement at a spacing of 85mm c/c. The RC beam specimen whose designation is B-2M85 stands for RC beam with shear spanto depth ratio of 3.0 and provided with 2M welded wire mesh as transverse (shear) reinforcement at a spacing of 85mm c/c. The details of specimens tested are given in Table.6.1 and typical WWM's and stirrup is shown in Fig. 6.2.The reinforcement cages used are shown in Fig.6.1.

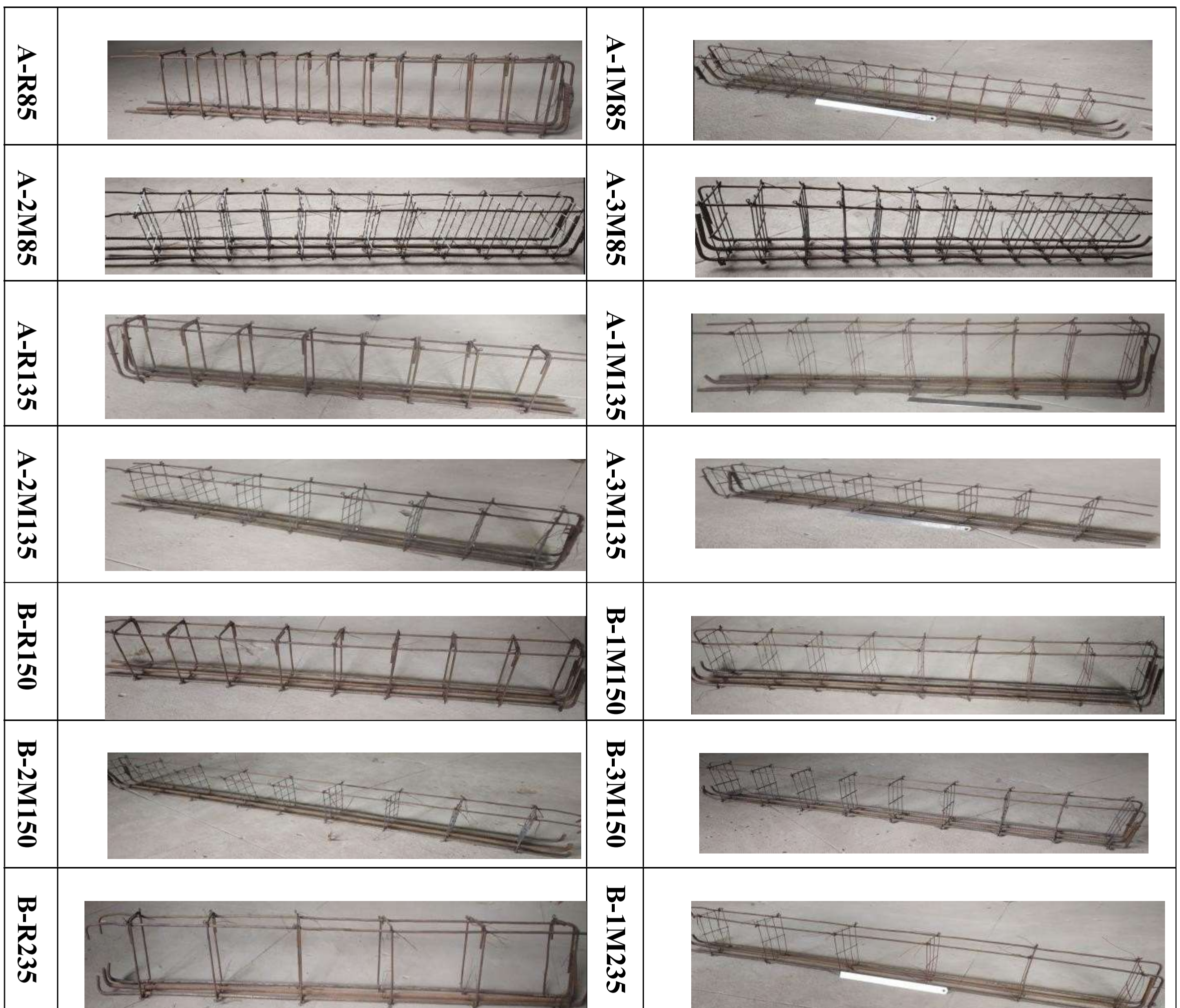


Fig.6.1 Reinforcement cages of 24 beams

B-2M235		**B-3M235**	
C-R240		**C-1M240**	
C-2M240		**C-3M240**	
C-R300		**C-1M300**	
C-M300		**C-M300**	

Fig.6.1 Reinforcement cages of 24 beams

The materials used for concrete consist of ordinary Portland cement of 53 grade confirming to IS 269-2015, the river sand as fine aggregate conforming to Zone-II of IS: 383 (2016), the coarse aggregate of 20mm nominal size, the potable water and super plasticizer. The specific gravity and density of sand are 2.65 & 1.45 g/cm3 respectively and that of coarse aggregate are 2.80 and 1.5g/cm3 respectively. The detail of concrete mix proportion is given in Table.6.2.

Table.6.1 Details of RC Beam specimens tested of Phase-III Beams

SNo	a/d	Beam	Transverse Reinforcement	Details of the Beam	
1.	**2.2**	A-R85	2 Lgd Stirrup @85 c/c	**For a/d=2.2:** Size of RC Beam- 125 x 205 x 1150 mm Effective depth (d) = 180 mm Shear span(a)=400 mm Effective Span (L) = 1000 mm Overall length = 1150 mm **For a/d=3.0:** Size of RC Beam- 125 x 205 x 1430 mm	**Concrete** Compression Strength= 34.8 MPa **Longitudinal Reinforcement** (Maintained constant in all the beams) 2-10mm dia and 1-12mm dia Yield Strength = 424 MPa Ultimate Strength = 538 MPa **Stirrup (R)** Diameter of Stirrup bar = 5.3mm
2.		A-1M85	1M-WWM @ 85 c/c		
3.		A-2M85	2M-WWM @ 85 c/c		
4.		A-3M85	3M-WWM @ 85 c/c		
5.		A-R135	2 Lgd Stirrup @ 135 c/c		
6.		A-1M135	1M-WWM @ 135 c/c		
7.		A-2M135	2M-WWM @ 135 c/c		
8.		A-3M135	3M-WWM @ 135 c/c		
9.	**3.0**	B-R150	2 Lgd Stirrup @ 150 c/c		
10.		B-1M150	1M-WWM @ 150 c/c		
11.		B-2M150	2M-WWM @ 150 c/c		
12.		B-3M150	3M-WWM @ 150 c/c		
13.		B-R235	2 Lgd Stirrup @ 235 c/c		
14.		B-1M235	1M-WWM @ 235 c/c		
15.		B-2M235	2M-WWM @ 235 c/c		
16.		B-3M235	3M-WWM @ 235 c/c		
17.	**3.8**	C-R240	2 Lgd Stirrup @ 240 c/c		
18.		C-1M240	1M-WWM @ 240 c/c		

Table.6.1 Details of RC Beam specimens tested of Phase-III Beams

SNo	a/d	Beam	Transverse Reinforcement	Details of the Beam	
19.		C-2M240	2M-WWM @ 240 c/c	Effective depth (d) = 180 mm Shear span(a)=540 mm Effective Span (L) = 1280 mm Overall length = 1430 mm **For a/d=3.8:** Size of RC Beam- 125 x 205 x 1720 mm Effective depth (d) = 180 mm Shear span(a)=690 mm Effective Span (L) = 1580 mm Overall length = 1730 mm	c/s Area of Stirrup bar = 22.05 sq.mm Yield Strength = 285.6 MPa Ultimate Strength= 361 MPa Average weight of each stirrup = 0.098 kg **Effective c/s Area of RC Beam** bd = 125 x 180 = 22500 sq.mm
20.		C-3M240	3M-WWM @ 240 c/c		
21.		C-R300	2 Lgd Stirrup @ 300 c/c		
22.		C-1M300	1M-WWM @ 300 c/c		
23.		C-2M300	2M-WWM @ 300 c/c		
24.		C-3M300	3M-WWM @ 300 c/c		

Table.6.1 (contd.) Details of RC Beam specimens tested

Details of Welded Wire Mesh (WWM) of size of the WWM used: 90mm x 180mm

Type of WWM	**1M**	**2M**	**3M**
No.of Vertical bars (Nv)	4	4	4
No. of horizontal bars (Nh)	3	5	3
Dia of Vertical bars (φv) in mm	1.9	2.16	4.16
c/s Area of Vertical bars (Av) in sq.mm	2.83	3.66	13.58
Dia of Horizontal bars (φh) in mm	1.7	2.16	2.5
c/s Area of Horizontal bar (Av) in sq.mm	2.27	3.66	4.91
Spacing of Vertical bars (Sv) in mm	30	30	30
Spacing of Horizontal bars (Sh) in mm	90	45	90
Yield strength (MPa)	386	330	347
Ultimate strength (MPa)	462	422	428
Average weight of the mesh (kg)	0.024	0.037	0.087
Percent weight of the WWM compared to the weight of stirrup	-75.5	-62.2	-11,2
Weld mesh factor (Wmf) = [(NvAv + Nh Ah) / Nv Av] x (bd/Sv Sh)	13.34	37.50	10.59

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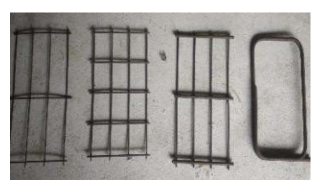


Fig.6.2 Typical WWM's and Stirrup

Table 6.2 Materials used (per Cu.m) of Phase-III Beams						
Concrete Grade	Mix Proportion	Quantity of concrete making materials Per Cu.m				
		Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)	SP* (kg)
M25	1: 1.9: 3.3 w/c 0.47	360	690	1180	170	2.7
*SP: Super plasticizer (SP 430, Make: Fosroc Chemicals)						

6.2.1. Casting and testing of RC beams

For casting the RC beams the steel channel moulds of required size were used. After placing the prefabricated reinforcement cages, the concrete was positioned in the moulds and compacted with vibrator. After 24 hours of casting, the beam specimens were de-moulded and water cured for a period of 28 days. The average room temperature and relative humidity measured during the period of curing were 35±2ºC and 75% are respectively. After the completion of curing period, the specimens were dispatched from the curing pond and kept under the shade. A day before testing the cured beams were white washed and marked on it with pencil the location of supports, the positions of deflection gauges during the test and kept ready for testing.

The beam specimens were tested under two-point loading (four-point bend test) by maintaining the required shear span to depth ratio, after a curing period of 28 days, on the TINUS – OLSEN testing machine of 2000 kN capacity. The deflection of the beam was measured and calculated using LVDT and deflection dial gauges. The details of test setup were shown in Fig.6.3. The displacement control loading was adopted by moving the loading cross head at a rate equal to 1/1500 of Span per minute (JSCE SF4,1985). The testing was continued till the point of ultimate load or the test set up reaches unstable position whichever is earlier. The cracks formed on the beams were noted and marked for comparison of crack pattern and nature of failure.

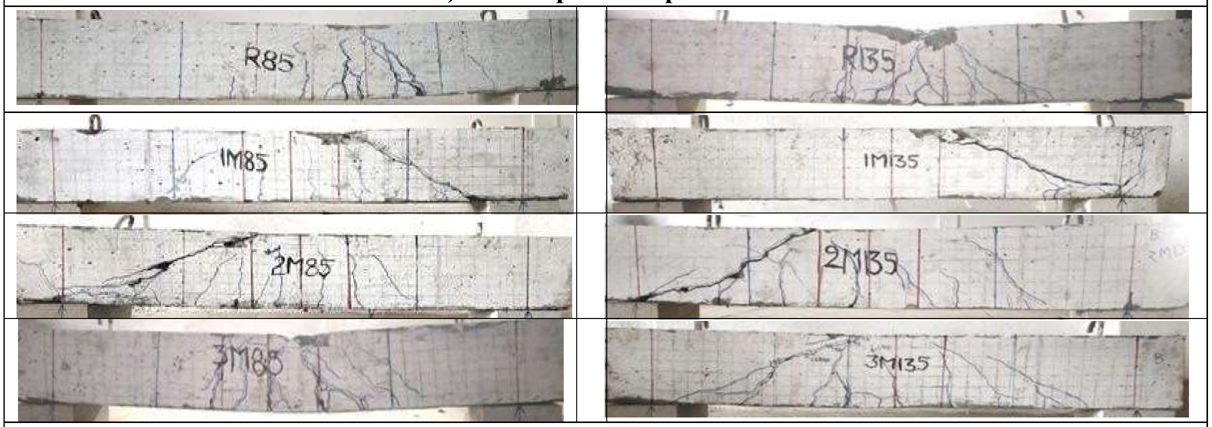
Fig. 6.3 Details of Test Setup

The Table 6.3 gives the experimentally recorded failure loads (Ultimate load), maximum deflections. The failure Configurations of the beam specimens are shown in Fig.6.4.

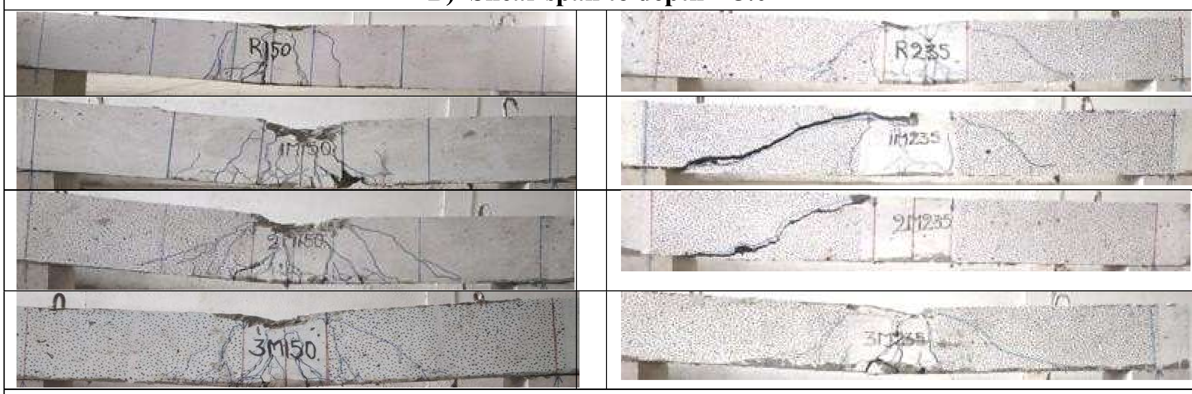
Table 6.3 Experimentally recorded loads and deflections of Phase-III

S.No	a/d	Beam	At Service		At Ultimate		Nature of failure At Ultimate
			Ps (kN)	ds (mm)	Pu (kN)	du (mm)	
18.	**2.2**	A-R85	71.81	3.91	107.71	8.6	Flexure
19.		A-1M85	72.11	3.82	108.17	8.4	Shear
20.		A-2M85	73.61	3.36	110.42	9.6	Shear
21.		A-3M85	74.09	3.09	111.14	11.2	Flexure
22.		A-R135	62.33	3.82	93.50	8.4	Flexure
23.		A-1M135	68.87	2.68	103.30	3.7	Shear
24.		A-2M135	69.67	3.18	104.51	9.2	Shear
25.		A-3M135	66.73	3.58	100.10	7.2	Flexure shear
26.	**3.0**	B-R150	42.67	4.55	64.01	14.4	Flexure
27.		B-1M150	37.67	4.00	56.50	15.4	Flexure
28.		B-2M150	40.23	4.23	60.35	11.5	Flexure shear
29.		B-3M150	53.83	4.95	80.75	13.1	Flexure
30.		B-R235	38.55	4.59	57.82	12.3	Flexure shear
31.		B-1M235	35.27	4.95	52.91	13.1	Shear
32.		B-2M235	36.73	4.23	55.10	7.1	Shear
33.		B-3M235	44.33	4.05	66.50	11.1	Flexure shear
34.	**3.8**	C-R240	37.87	5.59	56.80	16.7	Shear
35.		C-1M240	35.00	5.32	52.50	18.3	Flexure
36.		C-2M240	37.00	5.18	55.50	15.8	Shear
37.		C-3M240	43.53	5.91	65.30	17.4	Shear
38.		C-R300	35.27	5.14	52.90	24.5	Flexure
39.		C-1M300	34.53	5.91	51.80	16.4	Shear
40.		C-2M300	35.67	5.59	53.50	16.7	Flexure
41.		C-3M300	40.80	5.18	61.20	26.8	Shear

A) Shear span to depth = 2.2



B) Shear span to depth = 3.0



C) Shear span to depth = 3.8

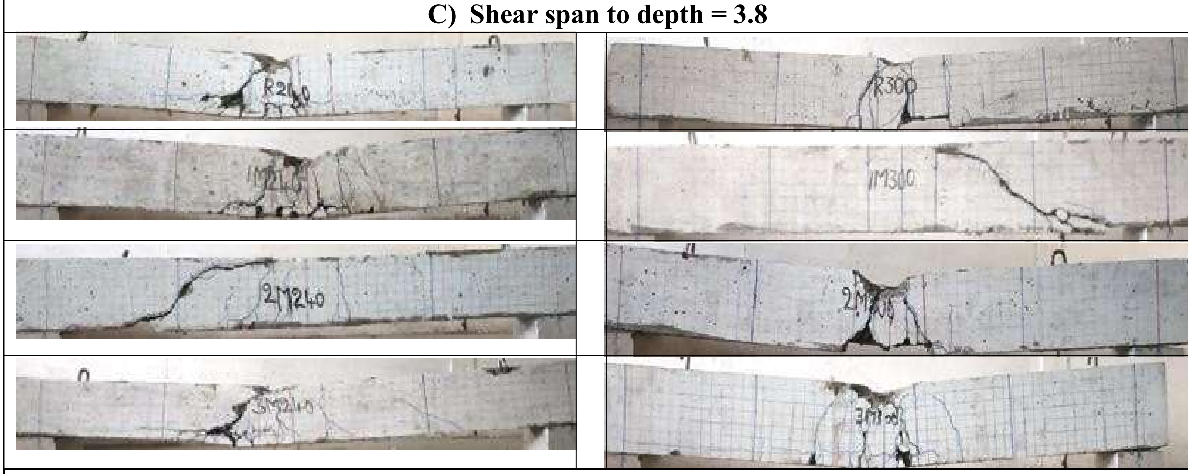


Fig.6.4 The failure patterns of the beam specimens

6.3. DISCUSSION OF BEHAVIOUR AND ANALYSIS OF TEST RESULTS

The observations made during the testing indicated that the increase in the shear span to depth ratio has been reduced the ultimate (failure) loads. It was noticed that the initial crack in all the specimens was a flexural crack that happened within the constant moment zone (i.e., between the loading points) and the increase in the load continued with the subsequent expansion of diagonal (shear) cracks propagated towards the loading points then after the cracks have occurred in the remaining elements of the beam. The average shear strength identified in beams with stirrups as transverse reinforcement is 50.30 kN, 30.45 kN and 27.42 kN for a/d equal to 2.2, 3 and 3.8 respectively. Whereas the average shear strength observed in beams with WWM as transverse reinforcement is 53.14 kN, 30.93 kN and 28.31 kN for a/d equal to 2.2, 3 and 3.8 respectively. This indicates that the average shear strengths of the beams provided with WWM as transverse reinforcement have always either equal to or more than the average shear strengths recorded in beams with stirrups as transverse. This happened even though the weight of the WWM compared to the weight of stirrup is less and thus indicate the effectiveness of WWM over the stirrups for the similar spacing's of the transverse reinforcements. The improvement in shear strength may be attributed to the effectiveness of mesh over conventional stirrups, in controlling / delaying the formation of shear crack. Hence it can be concluded that for the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM will be able to provide similar or better performance of RC beams compared to that of RC beams having conventional stirrups. This clearly indicates the effectiveness and economy of WWM over the conventional stirrups. Further, it can be concluded that the nature / behavior of the RC beam remained more or less similar with the replacement of conventional stirrups with welded wire mesh as transverse core zone reinforcement for the same spacing of transverse steel in the form of mesh / stirrups.

The observation of the deflections at service load is observed as 0.66 times the ultimate load, in all the tested beams is well within the permissible serviceability limits (i.e deflection less than Span/250) as per the existing Indian standard code of practice. Hence it can be considered that the use of WWM in place of conventional stirrups has not violated any serviceability criteria.

6.4. Analysis of test results and Mesh index

The experimental results presented above has indicated that even the less volume or weight of transverse steel in the form of mesh, which distribute uniformly across the cross section of RC beam performed better than conventional two-legged stirrups in enhancing the shear strength. Hence in order to quantify the influence of welded wire mesh as transverse core zone reinforcement in enhancing the shear resistance of RC beams, a simple and new parameter termed as 'Mesh index' has been proposed and quantified. The Mesh index (Km) proposed takes in to consideration indirectly the effect of the presence of horizontal wires (i.e the wires of the weld mesh parallel to the width of the RC beam) welded to the vertical wires in WWM in providing the shear resistance of RC beam having WWM as transverse reinforcement replacing the conventional stirrups. The mesh index proposed takes in to account the following three parameters related to the transverse reinforcement in the form of mesh / stirrups. The Mesh index parameters are presented in Table 6.4

Table 6.4 Representation of mesh index parameters of phase-III		
1. Area ratio	=	Ratio of total cross-sectional area of both vertical and horizontal bars to the cross-sectional area of only vertical bars of transverse steel (stirrup or mesh) = [(NvAv + Nh Ah) / Nv Av]
2. Distribution density	=	Distribution of transverse steel across the cross-section i.e., Number of apertures = bd/ (Sv Sh)
3. Spacing ratio	=	Spacing of transverse steel to the effective depth = S/d

Weld mesh factor (Wmf) = Area ratio x Distribution density

$$\text{Mesh Index (Mi)} = \frac{\text{Weld mesh factor}}{\text{Spacing ratio}} = \frac{[(NvAv + Nh\,Ah) / Nv\,Av]\,(bd/Sv\,Sh)}{S/d}$$

The following simplified analysis has been carried out based on the philosophy of the current shear design practice adopted in the structural concrete design codes [2, 18 and 19]. In general, the mechanism of shear resistance in RC beams is based on the parallel chord truss analogy. As per the truss analogy, the web of corresponding truss consists of web reinforcement acting as tension members and concrete struts acts parallel to the inclined cracks formed in the presence of shear. The concrete compression zone and the flexural reinforcement form the upper and bottom chords of the truss. For a beam with web reinforcement the shear resistance may be regarded as the sum of the concrete resistance and the web steel resistance. Following the truss analogy, the shear resistance of the RC beam provided with transverse reinforcement (either in the form of conventional stirrups WWM) can be written as

$$Vu = Vc + Vs,$$

Where Vc = Concrete shear resistance offered without any web reinforcement calculated as per IS 456.

Vs = Shear resistance offered by the web steel in the form of stirrups or WWM = K fyv Av d / Sv,

where fyv = Yield strength of stirrup or mesh wires, Av = Cross sectional area of all vertical bars of the stirrup or the weld mesh,

Sv = spacing of the transverse reinforcement in the form of stirrups or WWM along the length of the beam.

K= A factor accounting for the effect transverse reinforcement in the form of stirrups or WWM**.**

Hence, Vs = Vu – Vc = (K fyv Av d / Sv).

On simplifying, K = [(Vu-Vc) Sv/d] / fyv Av

From the experimental results the value of K has been evaluated for different mesh index (Mi) and are given in Table 6.5

The variation of K factor with Mesh index is shown in Fig.6.4 for different a/d ratios. It is observed from the Fig.6.5, that there is a large scatter K factor values with mesh index for a/d=2.2. However, there exist a good correlation of K factor values with mesh index for a/d >2.5. The best fit equation relating the K factor and mesh index for different a/d ratios proposed are as follows.

For a/d < 2.5	For a/d > 2.5
$K = 0.488\ (Mi)^{0.43}$ $R^2 = 0.318$	$K = 0.305\ (Mi)^{0.33}$ $R^2 = 0.958$

Using the above proposed K factor, the ultimate load has been calculated as follows and are tabulated in Table 6.5.

$$P_{u,cal} = 2\ V_u = 2\ (V_c + V_s) = 2(\ V_c + K\ f_{yv}\ A_v\ d / S_v)$$

Table 6.5 K factor for different Mesh index of Phase-III beams

a/d	Beam	Mi	Pu, exp (kN)	Vu	Vc	fy	Av	Sv/d	K
2.2	A-R85	5.88	107.71	53.86	27.46	309	44.10	0.47	0.915
	A-1M85	28.24	108.17	54.09	27.46	386	11.34	0.47	2.873
	A-2M85	79.41	110.42	55.21	27.46	330	14.65	0.47	2.711
	A-3M85	22.43	111.14	55.57	27.46	347	54.34	0.47	0.704
	A-R135	3.70	93.50	46.75	27.46	309	44.10	0.75	1.062
	A-1M135	17.78	103.30	51.65	27.46	386	11.34	0.75	4.146
	A-2M135	50.00	104.51	52.26	27.46	330	14.65	0.75	3.846
	A-3M135	14.12	100.10	50.05	27.46	347	54.34	0.75	0.898
3.0	B-R150	3.33	64.01	32.00	24.17	309	44.10	0.83	0.479
	B-1M150	16.00	56.50	28.00	24.17	386	11.34	0.83	0.730
	B-2M150	45.00	60.35	30.00	24.17	330	14.65	0.83	1.005
	B-3M150	12.71	80.75	40.35	24.17	347	54.34	0.83	0.715
	B-R235	2.13	57.82	28.90	24.17	309	44.10	1.31	0.453
	B-1M235	10.22	52.91	26.45	24.17	386	11.34	1.31	0.681
	B-2M235	28.72	55.10	27.55	24.17	330	14.65	1.31	0.914
	B-3M235	8.11	66.50	33.25	24.17	347	54.34	1.31	0.629
3.8	C-R240	2.08	56.80	28.40	24.17	309	44.10	1.33	0.414
	C-1M240	10.00	52.50	26.25	24.17	386	11.34	1.33	0.635
	C-2M240	28.13	55.50	27.75	24.17	330	14.65	1.33	0.988
	C-3M240	7.94	65.30	32.65	24.17	347	54.34	1.33	0.600
	C-R300	1.67	52.90	26.45	24.17	309	44.10	1.67	0.279
	C-1M300	8.00	51.80	25.90	24.17	386	11.34	1.67	0.660
	C-2M300	22.50	53.50	26.75	24.17	330	14.65	1.67	0.890
	C-3M300	6.35	61.20	30.60	24.17	347	54.34	1.67	0.569

Correlation between experimental and calculated ultimate loads is: 0.493 for a/d < 2.5 and 0.997 for a/d >2.5

Note:	
Vu = Shear force = Pu/2	$V_c = (0.21/\beta)(\sqrt{0.8\, f_{ck}}((1+5\beta)-1)\, bd$ for a/d >2.5
K = [(Vu-Vc) Sv/d] / fyv Av	$V_c = (2.5/a/d)(0.21/\beta)(\sqrt{0.8\, f_{ck}}((1+5\beta)-1)\, bd$ for a/d <
	$\beta = 0.8 f_{ck}/ 6.89\, \rho$ where $\rho = 100\, A_{st}/bd$ = percent of Lon

The correlation between experimental and calculated ultimate loads is 0.493 and 0.997 for a/d <2.5 and a/d >2.5 respectively. Hence mesh index criteria may not be able to estimate the true shear strength of RC beams for a/d = 2.2. This may be attributed to the fact that the shear resistance of RC beams for a/d < 2.5 is in general governed by the arch action which is dependent on the strength of concrete compressive strut and the tensile strength of longitudinal steel. Further it has been reported that in RC beams with a/d <2.5, the use of vertical transverse steel may not effectively restrain the critical diagonal crack opening and thus the contribution of conventional vertical shear reinforcement to the shear resistance of beams decreases as the shear span-to-depth ratio of beams reduces (Chalachew, 2021). For RC beams with a/d > 2.5, the shear strength is governed by the beam action which include the truss mechanism apart from interlocking of aggregates and dowel action. Thus, the vertical transverse reinforcement either in the form of stirrups or WWM is able to provide better shear resistance in RC beams with a/d >2.5.

The above discussion on the behavior of the beams have clearly indicated the better performance of the weld mesh as transverse reinforcement over the conventional stirrups for the same spacing from the point of shear strength and economy in the required quantity of transverse steel. However, the effect of mesh index needs to be further investigated for strength of concrete and percent of longitudinal steel other than those adopted in the present investigation and particularly for shear span to depth ratios less than 2.5.

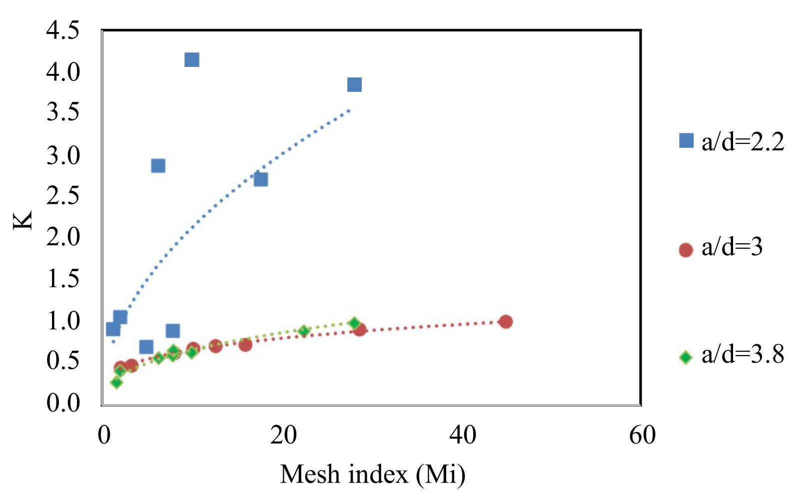


Fig.6.5 Variation of K factor with Mesh index of Phase-III

6.5. Conclusions

The following are the conclusions arrived at after the study of welded wire mesh as transverse reinforcement replacing the conventional stirrups in RC beams with different shear span to depth (a/d) ratios.

1) The failure pattern of RC beams provided with welded wire mesh as transverse reinforcement is more or less similar to the RC beams provided with conventional stirrups for the same spacing of transverse steel irrespective of the a/d ratio.
2) For the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM is able to provide similar or better ultimate load capacity of RC beams compared to that of RC beams having conventional stirrups irrespective of the a/d ratio.
3) The mesh index – a new parameter proposed which takes in to account the area ratio, distribution density and spacing ratio of the transverse reinforcement provided in the form of stirrups or WWM, can be used in estimating the ultimate loads with more accuracy in the case of RC beams with shear span to depth ratio greater than 2.5.
4) In all the RC beams tested irrespective of a/d ratio, the satisfactory serviceability behavior together with reduced consumption of transverse steel justifies the use of welded wire mesh over the conventional stirrups as transverse reinforcement for the same spacing of transverse steel.

Chapter 7

NUMERICAL SIMULATION OF RC BEAMS PROVIDED WITH WWM AS SHEAR REINFORCEMENT USING ABAQUS

Chapter 7

NUMERICAL SIMULATION OF RC BEAMS PROVIDED WITH WWM AS SHEAR REINFORCEMENT USING ABAQUS

7.1. General

In the earlier, three phases of experimental investigation were described and it was concluded that the WWM as a transverse reinforcement in RC beams is able to provide similar or better ultimate load capacity compared to that provided by the conventional stirrups. Of late the ABAQUS software is majorly preferred in the simulation of engineering problems. The availability of extensive library of different material models, boundary conditions, the facility to specify component interactions and convergence tolerances have made the ABAQUS a suitable finite element tool in providing solutions not only to the structural analysis problems but also to the non-structural problems. Hence in this phase of investigation, the numerical simulation of reinforced concrete beams provided with WWM as shear reinforcement is attempted by modelling the same using ABAQUS software. The results arrived from ABAQUS were compared with the experimental results presented in the earlier phases of investigation. A total of thirty (30) RC beams of the following types were modelled in ABAQUS.

i) 6 numbers of RC beams of phase-1 experimental investigation representing single type of WWM as core zone transverse reinforcement with constant shear span to depth ratio of 3 and

ii) 24 numbers of RC beams of phase-3 experimental investigation representing three different types of WWM as core zone transverse reinforcement with three different shear spans to depth ratios.

7.2 Concrete Damaged Plasticity Model: ABAQUS/ CAE used to analyze and interpret results in three constitutive models like Brittle Cracking Model, Smeared Cracking Model and Damaged Plasticity Model of concrete. These models are utilized to model on Plain concrete, Quasi –brittle materials and reinforced concrete structures like beams, solids, trusses and solids. Among three available constitutive models, the concrete damaged plasticity model is found to fit the purpose best. Several parameters are investigated, such as finite element size, concrete strength properties, modulus of elasticity, and the type of boundary conditions. The Concrete Damage Plasticity model needs a concrete uniaxial compressive stress-strain, concrete uniaxial tensile stress-strain and compressive damage parameters as input to perform modeling in FE simulation. The concrete damage parameters consist of cracking strain, crushing strain, tensile plastic strain, compressive plastic strain, tensile damage parameter (dt), and compressive damage parameters (dc), dilation angle(Ψ), flow potential eccentricity (€), ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (σbo/σco), Kc, viscosity parameter(μ) are presented in Table 7.2. The concrete compressive and tensile behavior can be clearly depicted from this model.

7.3 Numerical analysis using ABAQUS

In this numerical investigation ABAQUS/ CAE-6.14 of concrete damaged plasticity model applicable to the quasi-brittle materials was used where both tension and compression behavior under cracking can be studied. All the RC beams are modelled in different sequential modules are explained below:

7.3.1 Part module- Creating the Part:

Reinforced concrete beams of cuboidal shape of four different size beams were modelled covering 30 beams and experimental conducted and presented in chapter 4 and 6. For geometrical modelling, variables it depends on cross sectional dimensions of beam, diameters of longitudinal and transverse reinforcement, diameters of mesh wires and details of 30 beams are presented in Table 7.1. Concrete beam is modelled as 3D deformable solid extrusion type. Flexural and shear steel reinforcement of circular shape with different diameters are modelled as 3D deformable wire planar type.

7.3.2 Property Module-Assigning the property materials:

In this module, each part is selected and use to assign respective properties which include concrete properties like density, young's modulus, poisson's ratio, compression damage and tension damage parameters, yield stress and elastic strain are provided considering the section as solid homogeneous and above variable details are presented in Table 7.3. Similarly for steel properties like density, young's modulus, poisons ratio, yield stress and plastic strain are provided for both Fe250 and Fe500 considering the truss and the steel properties are presented in Table 7.4.

7.3.3 Assembly Module-Assemble all the parts:

This module helps to unite all the individual parts modelled in part module. Individual parts are assembled to form the required section which is in global coordinates converted from local coordinates of individual parts like steel reinforcement, welded wire mesh /stirrups are embedded into the plain concrete beam. In this present work, few beams are modelled as regular

Table 7.1. Details of Numerically investigated beams with its cross section and diameter of longitudinal and transverse steel bars and welded wire mesh diameters.

Shear span to Depth ratio (a/d)	Beams	Details	Dimensions	Tension Reinforcement Diameters	Compression Reinforcement Diameters	Shear Reinforcement Details
Phase-I Beams						
3.0	R160	2 Lgd 6Φ @160 c/c	140mm x 240mm x1650mm	2-12Φ & 1-16Φ	2-6Φ	Stirrup Diameter = 5.3mm
	R100	2 Lgd 6Φ @100 c/c		2-12Φ & 1-16Φ	2-6Φ	See WWM table below
	R60	2 Lgd 6Φ @60 c/c		2-12Φ & 1-16Φ	2-6Φ	
	M160	WWM @160 c/c		2-12Φ & 1-16Φ	2-6Φ	
	M100	WWM @100 c/c		2-12Φ & 1-16Φ	2-6Φ	
	M60	WWM @60 c/c		2-12Φ & 1-16Φ	2-6Φ	

Type of WWM	M
No.of Vertical bars (Nv)	5
No. of horizontal bars (Nh)	5
Spacing of Vertical Wires	50mm
Spacing of Horizontal Wires	30mm
Diameter of Vertical wire	2.34mm
Diameter of Horizontal wire	2.34mm
Yield strength of Wires	267.7 MPa
Ultimate Strength of Wires	347 MPa.

Shear span to Depth ratio (a/d)	Beams	Details	Dimensions	Tension Reinforcement Diameters	Compression Reinforcement Diameters	Shear Reinforcement Details
Phase-III Beams						
2.2	A-R85	2 Lgd Stirrup @85 c/c	125mm x 205mm x 1150 mm	2-10Φ & 1-12Φ	2-6Φ	See WWM table below
	A-1M85	1M-WWM @ 85 c/c		2-10Φ & 1-12Φ	2-6Φ	
	A-2M85	2M-WWM @ 85 c/c		2-10Φ & 1-12Φ	2-6Φ	
	A-3M85	3M-WWM @ 85 c/c		2-10Φ & 1-12Φ	2-6Φ	
	A-R135	2 Lgd Stirrup @ 135 c/c		2-10Φ & 1-12Φ	2-6Φ	
	A-1M135	1M-WWM @ 135 c/c		2-10Φ & 1-12Φ	2-6Φ	
	A-2M135	2M-WWM @ 135 c/c		2-10Φ & 1-12Φ	2-6Φ	

Type of WWM	1M	2M	3M
No.of Vertical bars (Nv)	4	4	4

Shear span to Depth ratio (a/d)	Beams	Details	Dimensions	Tension Reinforcement Diameters	Compression Reinforcement Diameters
	A-3M135	3M-WWM @ 135 c/c		2-10Φ & 1-12Φ	2-6Φ
3.0	B-R150	2 Lgd Stirrup @ 150 c/c	125mm x 205mm x 1430 mm	2-10Φ & 1-12Φ	2-6Φ
	B-1M150	1M-WWM @ 150 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-2M150	2M-WWM @ 150 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-3M150	3M-WWM @ 150 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-R235	2 Lgd Stirrup @ 235 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-1M235	1M-WWM @ 235 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-2M235	2M-WWM @ 235 c/c		2-10Φ & 1-12Φ	2-6Φ
	B-3M235	3M-WWM @ 235 c/c		2-10Φ & 1-12Φ	2-6Φ
3.8	C-R240	2 Lgd Stirrup @ 240 c/c	125mm x 205mm x 1720 mm	2-10Φ & 1-12Φ	2-6Φ
	C-1M240	1M-WWM @ 240 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-2M240	2M-WWM @ 240 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-3M240	3M-WWM @ 240 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-R300	2 Lgd Stirrup @ 300 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-1M300	1M-WWM @ 300 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-2M300	2M-WWM @ 300 c/c		2-10Φ & 1-12Φ	2-6Φ
	C-3M300	3M-WWM @ 300 c/c		2-10Φ & 1-12Φ	2-6Φ

Shear Reinforcement Details

No. of horizontal bars (Nh)	3	5	3
Dia of Vertical bars (φv) in mm	1.9	2.16	4.16
Dia of Horizontal bars (φh) in mm	1.7	2.16	2.5
Spacing of Vertical bars (Sv) in mm	30	30	30
Spacing of Horizontal bars (Sh) in mm	90	45	90
Yield strength (MPa)	386	330	347
Ultimate strength (MPa)	462	422	428

conventional beam with stirrups and another few beams are modelled as stirrups beams with welded wire mesh as transverse reinforcement replacing the stirrups of assembled ones are presented in fig.7.1(a)(b)(c). By using repeat instance specially with linear pattern welded wire mesh is created.

Table 7.2 Concrete Damage Plasticity parameters

Dilation angle(Ψ)	Flow potential eccentricity (€)	σbo/σco	Kc	Viscosity parameter(μ)
31	0.1	1.16	0.67	0.002

Table 7.3 Concrete Properties

Compression Behavior			
Yield stress	**Compressive plastic strain**	**Compressive damage parameters (dc)**	**crushing strain**
12.983	0	0	0
13.497	0.3E-05	0.001	0.3E-05
15.096	2.1E-05	0.006	2.1E-05
16.588	4.4E-05	0.012	4.4E-05
17.998	7.1E-05	0.021	7.1E-05
26.000	65.8E-05	0.193	65.8E-05
21.984	136.6E-05	0.398	136.6E-05
12.948	233.2E-05	0.673	233.2E-05
10.654	255.0E-05	0.735	255.0E-05
5.616	301.0E-05	0.864	301.0E-05
Tensile Behavior			
Yield stress	**Tensile plastic strain**	**Tensile damage parameter (dt)**	**cracking strain**
2.49	0	0	0
1.75	0.5E-04	0.11	0.5E-04
0.75	2.0E-04	0.381	2.0E-04
0.01	10.0E-04	0.95	10.0E-04
Elastic Properties			
Young's modulus		**Poisson ratio**	
25000		0.2	

Table 7.4 Steel and Welded Wire Mesh Properties

Fe250	
Yield stress	**Plastic strain**
165.00	0
172.29	3.032E-06
191.56	6.859E-06
217.62	7.867E-06
Elastic Properties	
Young's modulus	**Poisson ratio**
201221	0.3
Fe500	
Yield stress	**Plastic strain**
347.314	0
373.057	1.218E-04
391.567	2.961E-04
405.485	5.184E-04
416.731	7.609E-04
425.956	10.246E-04
431.421	13.448E-04
434.246	16.732E-04
436.167	19.448E-04
436.595	19.866E-04
Elastic Properties	
Young's modulus	**Poisson ratio**
200760	0.33

7.3.4 Step Module -Analysis step:

Step module organizes the analysis process with two main step groups. Basic step is initial which is created only when the model gets started. Another one is analysis step for the mode of analysis with different types of conditions and status can be observed weather it is created or progressing. Number of steps are divided into smaller steps which resembling the additional load provided in the actual experimental program. In the present work static, general condition is selected. It also helps to define field ouput parameters like displacement, forces, DAMAGEC and DAMAGET(Concrete damage plasticity parameters).

7.3.5 Interaction module:

In this module, complete mechanical contact is established between the individual parts, as assemble module is not enough to form as a single unit. Hard and frictional contact is maintained till the completion of analysis process. The interaction provided between different sections of developed beam is presented in fig 7.1(d) and the constraints are provided as embedded region type.

7.3.6 Loading module-Defining and assigning the loads:

Loads and boundary conditions at top and bottom of the member can be assigned. The boundary condition manager organizes the boundary condition progress like created or propagated. In this, two boundary conditions are created such that boundary condition at bottom is indicated as BC-1 is selected as pinned condition having (U1=U2=U3=0) which is coordinated by initial step. Boundary condition at top is designated as BC-2 is selected as displacement/rotation reflecting the applied load and organized by step-1 from step module. The application of loads and pinned support is presented in fig 7.1(e).

7.3.7 Mesh Module-Meshing the parts:

This module is the crucial module where simulation of the member can be performed. It helps to discretize member into number of finite elements of different shapes, sizes and elements are formed. Each finite element is analyzed to get simulation results. In this modelling, most of the concrete beams are meshed with a global size of 15 with 4-noded plane stress element (CPS4R). Reinforcement are meshed with a standard truss element of 2-noded linear 3D truss(T3D2) of global size as 20 is selected to perform analysis. The mesh sensitivity is verified with different finite elements and the meshing of the sample beam is presented in fig 7.1(f).

7.3.8 Job Module-Run Analysis:

In this module, all the input data was submitted and the model get run for full analysis. Before performing the analysis, it checks the missing data, if it founds error will be observed. In this monitoring of complete analysis process can be observed and fallowed by output database.

7.3.9 Visualization Module:

This module completely presents the output data that was selected in step module like load-deflection curves, stress-strain curves and member deformation behavior can be observed.

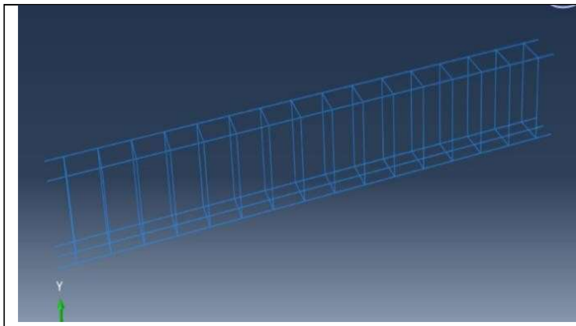
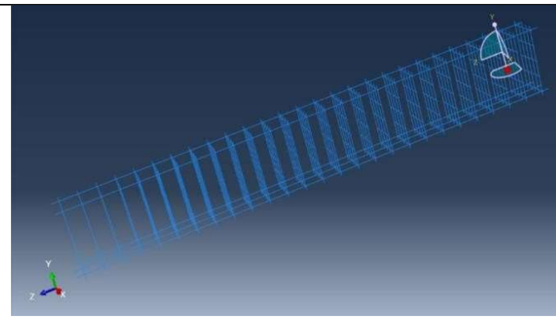
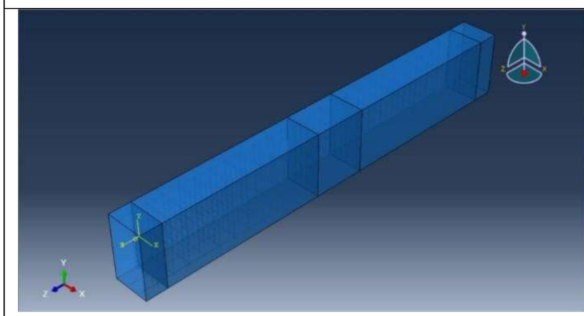
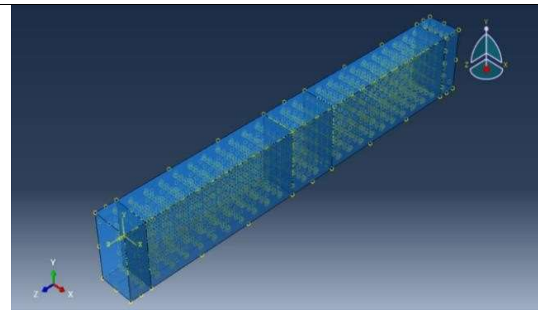
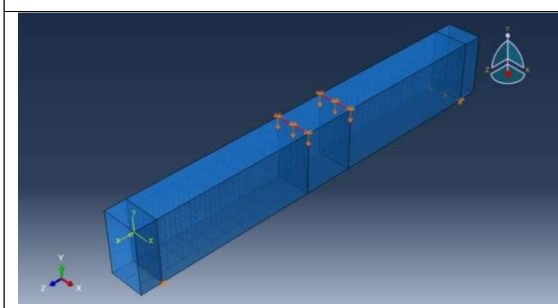
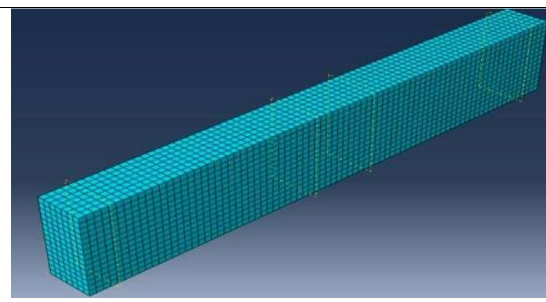
	
(a) Assembled Regular beam	(b) Assembled transverse mesh
	
(c) Assembled RC beam	(d) Interaction of transverse beam
	
(e) Loading setup	(f) Meshing of the beam

Fig. 7.1 Representation of different modules

7.4 Numerical simulation of RC beams with WWM as core zone transverse reinforcement for constant shear span to depth ratio of 3 of phase-I beams

After conducting the sequence of modules in ABAQUS providing all input data required, the output data is observed in visualization mode after fulfilling the job module. One of the output parameters is about failure patterns and these patterns are presented in the form of compression and tension cracking mode. The Experimental program of six beams are explained in chapter 4. The Comparative Results of Experimental and Numerical loads, deflections and also their percentage differences are shown in Table 7.5. The failure patterns of all these six beams are compared with experimental failure patterns and are presented in fig 7.2.

Table 7.5 Comparative results of experimental and numerical loads and deflections of phase-I beams

Model	M60	R60	M100	R100	M160	R160
Experimental ultimate load(KN)	206.1	166.42	181.55	166.45	138.05	136.92
Experimental deflection (mm)	8.41	8.65	12.7	10.5	5.46	7.1
Numerical ultimate load(KN)	197.43	178.32	190.04	178.06	155.95	144.86
Numerical deflection (mm)	7.99	7.90	12.71	8.83	5.98	6.93
Percentage difference of Experimental to Numerical ultimate load	4.2%	7.15%	4.67%	6.97%	12.9%	5.8%
Percentage difference of Experimental to Numerical Deflection	4.98%	8.64%	0.1%	15.9%	9.6%	2.26%

7.4.1 Load-Deflection curves of phase-I beams:

Taking the Phase-I Experimental six beams results at all points and the numerical results from visualization mode is presented in graphical form for better understanding of variation between numerical and experimental are presented in Fig 7.3 which indicates a good correlation between the observed load - deflection in experiments and that obtained through the numerical models created in ABAQUS FEA software. In Load-Deflection curves, R/M indicates conventional beams or welded wire mesh fallowed by spacing and representation of experimental(E)/ Numerical(A). As Numerical results are close to experimental results, also proved the superior performance of welded wire mesh over the conventional beams and with the reduction of spacing improves the load carrying capacity of the beams.

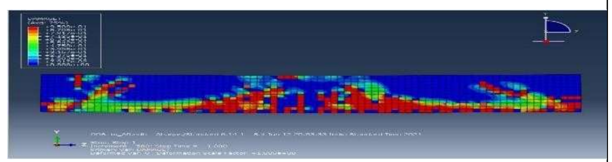
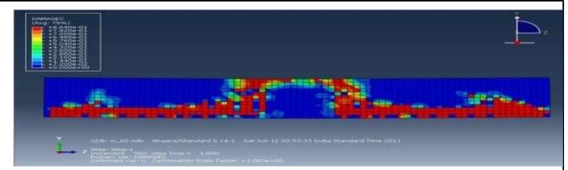
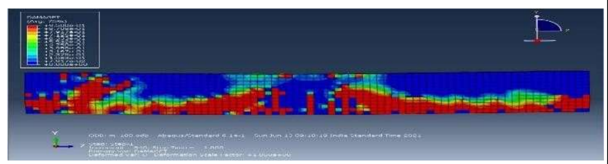
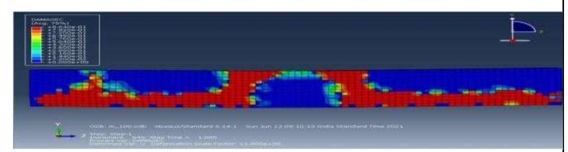
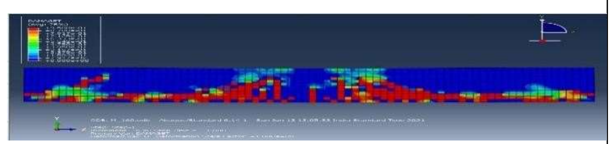
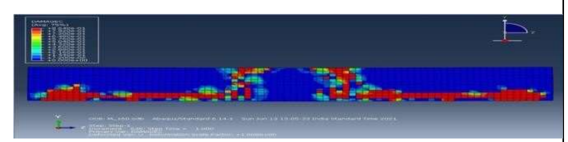
RC Beam	**Experimental failure pattern**	**Damage Pattern in tension in ABAQUS**	**Damage Pattern in compression in ABAQUS**
M60			
M100			
M160			

Fig. 7.2 Phase-I Experimental and numerical beams with Tensile and compressive damage patterns for constant shear span to depth ratio of 3

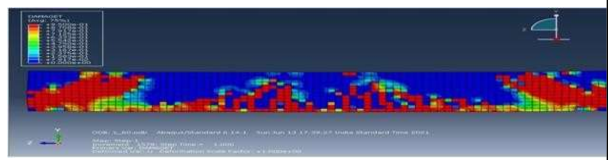
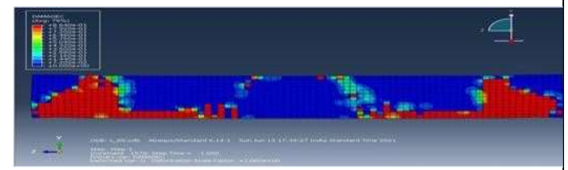
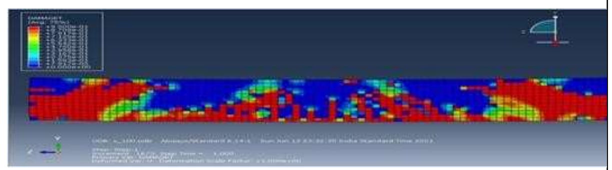
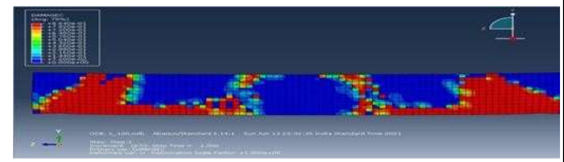
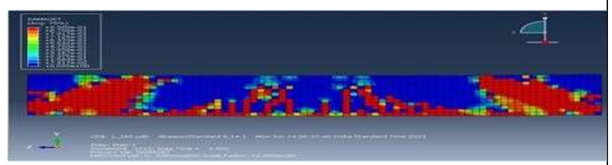
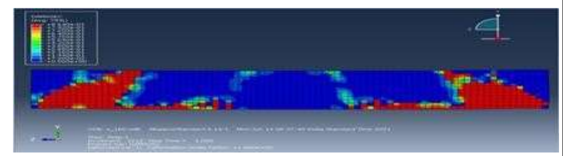
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
R60			
R100			
R160			

Fig. 7.2 Phase-I Experimental and numerical beams with Tensile and compressive damage patterns for constant shear span to depth ratio of 3

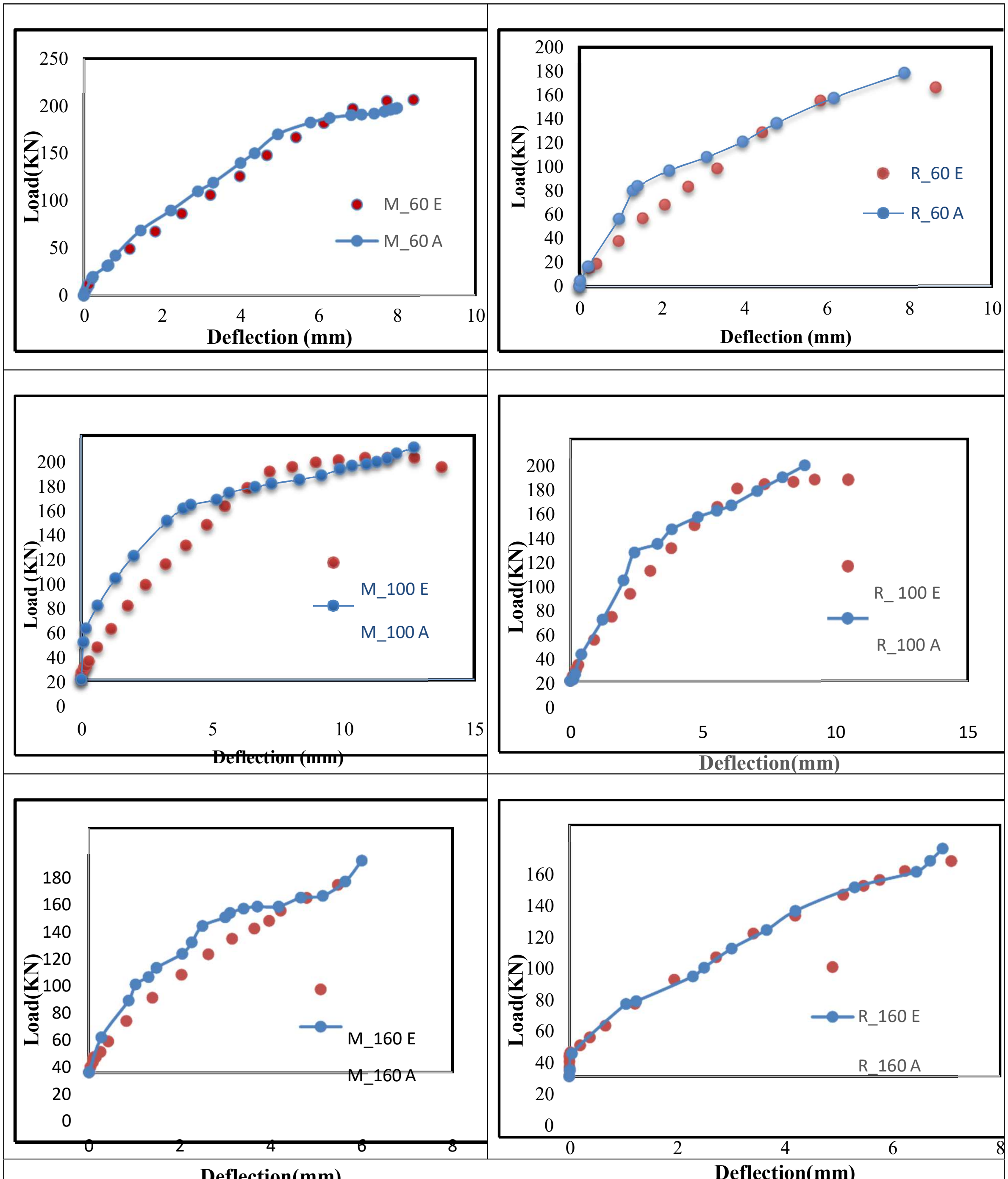


Fig 7.3 Graphical comparison of Phase-I beams of Experimental and numerical load deflection curves

7.5Numerical simulation of RC beams of three different WWM as core zone transverse reinforcement for three different shear span to depth ratios

From previous numerical investigation, beams with welded wire mesh are performed better compared to conventional beams and this investigation is limited to single shear span to depth ratio 3. Now the numerical study is conducted for the extension of above program, where mesh effect is clearly studied by considering three different meshes indicated as 1M,2M and 3M for shear span to depth ratios of 2.2,3,3.8. Experimentally, it was analyzed and proved in chapter-6 indicated as phase-3 experimental program. Numerically the beams are developed by fallowing above mentioned sequential modules and results from visualization are presented and compared with experimental results. Indication and explanation of each beam under this numerical investigation can be identified from table 7.1. In the present Experimental program, three a/d ratios are considered as 2.2, 3,3.8 such two spacing's are selected for each a/d based on required spacing's. For a/d ratio 2.2, spacing which is less than required(S1) is 85mm and greater than required (S2) is 135mm. Similarly, for a/d ratio 3, S1 is taken as 150mm and S2 is 235mm and for a/d ratio of 3.8, S1 is 240mm and S2 is 300mm.The Comparative Results of Experimental and Numerical loads, deflections and also their percentage differences are shown in Table 7.6, 7.7 and 7.8 for three different shear span to depth ratios 2.2,3, 3.8 respectively. The failure patterns of all 24 beams are compared with experimental failure patterns are presented in fig 7.4, 7.5 and 7.6.

Table 7.6 Comparative results of experimental and numerical load deflection values for a/d=2.2

Model	A-R85	A-1M85	A-2M85	A-3M85	A-R135	A-1M135	A-2M135	A-3M135
Experimental ultimate Load(KN)	106.9	105.2	110.4	104	112	76.9	110.9	110.5
Experimental Deflection(mm)	8.6	8.4	9.6	11.2	8.4	3.7	9.2	7
Numerical ultimate Load(KN)	110.42	111.15	107.73	108.17	104.52	78.77	103.3	105.93
Numerical deflection(mm)	8.22	8.52	9.53	10.82	7.83	4.16	8.55	6.35
Percentage difference of Numerical ultimate load	3.3%	5.64%	2.41%	4.01%	6.68%	2.41%	6.85%	4.13%
Percentage difference of Numerical deflection	4.45%	1.38%	0.71%	3.35%	6.76%	12.53%	7.02%	9.26%

Table 7.7 Comparative results of experimental and numerical load deflection values for a/d=3

Model	B-R150	B-1M150	B-2M150	B-3M150	B-R235	B-1M235	B-2M235	B-3M235
Experimental ultimate Load(KN)	100.3	94.9	75.8	66.7	75.2	66.7	63.8	76.1
Experimental Deflection(mm)	14.4	15.4	11.5	13.1	12.3	13.1	7.1	11.1
Numerical ultimate Load(KN)	90.93	95.72	82.81	71.61	72.42	69.51	64.53	80.51
Numerical deflection(mm)	13.34	14.38	11.42	12.59	11.47	12.75	6.43	10.31
Percentage difference of Numerical ultimate load	5.24%	0.85 %	9.24%	7.36%	6.38%	4.22%	1.14%	5.79%
Percentage difference of Numerical deflection	7.36%	6.62%	0.70 %	3.89%	6.74%	2.67%	9.33%	7.11%

Table 7.8 Comparative results of experimental and numerical load deflection values for a/d=3.8

Model	C-R240	C-1M240	C-2M240	C-3M240	C-R300	C-1M300	C-2M300	C-3M300
Experimental ultimate Load(KN)	52.7	64.7	65.5	60.4	44.5	51	55.9	65
Experimental Deflection(mm)	16.7	18.3	15.8	17.4	24.5	6.4	16.7	26.8
Numerical ultimate Load(KN)	55.54	66.91	68.43	62.63	47.41	53.52	58.83	68.31
Numerical deflection(mm)	15.91	17.97	15.77	16.11	23.94	6.47	17.01	25.91
Percentage difference of Numerical ultimate load	5.38%	3.4%	4.47%	3.67%	6.53%	4.94%	5.24%	5.09%
Percentage difference of Numerical deflection	4.71%	1.8%	0.19%	7.41%	2.28%	1.13%	1.88%	3.30%

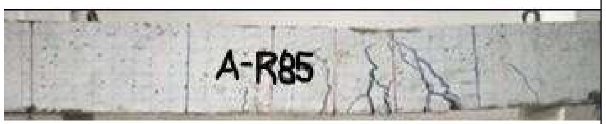
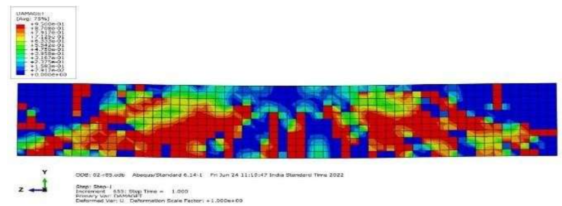
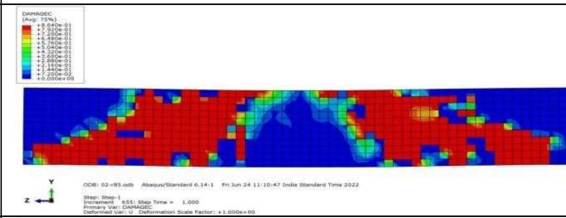
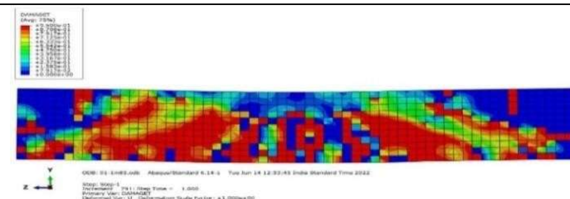
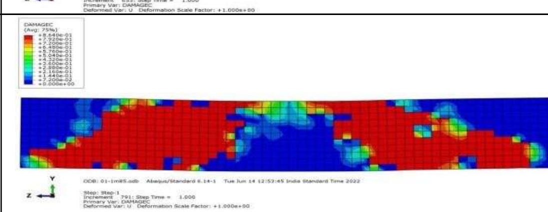
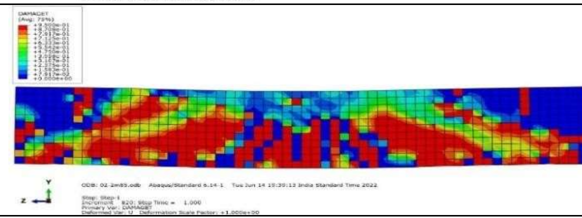
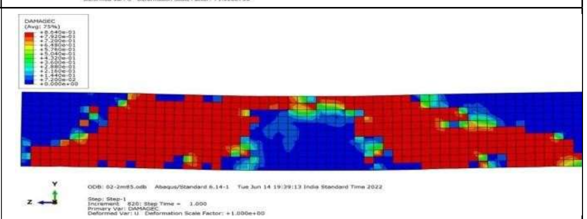
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
A-R85			
A-1M85			
A-2M85			

Fig. 7.4 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of2.2

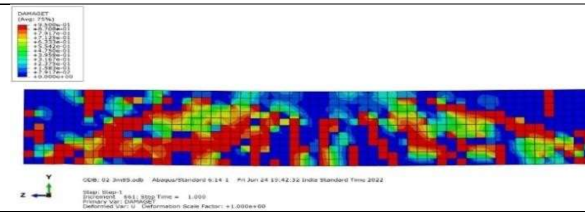
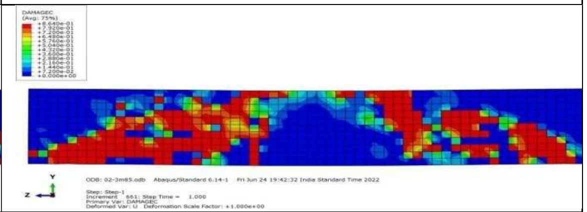
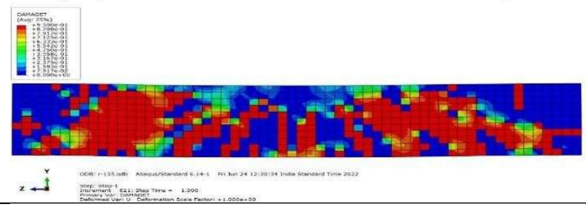
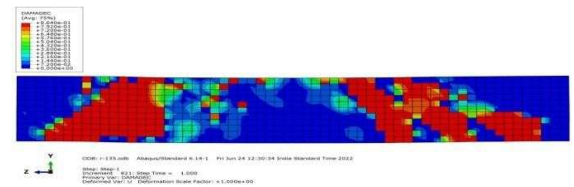
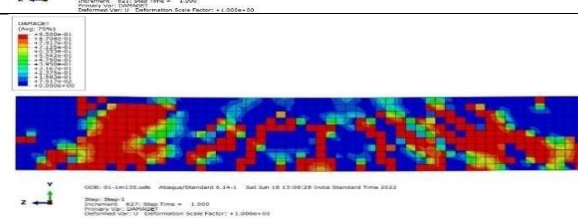
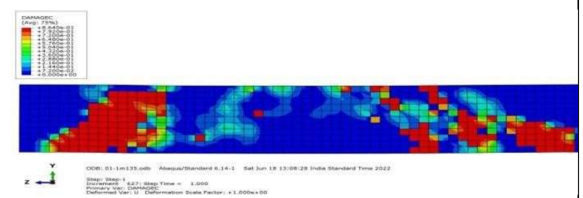
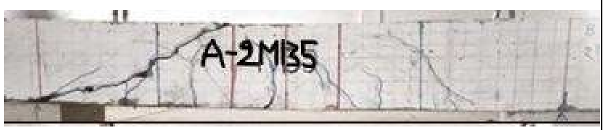
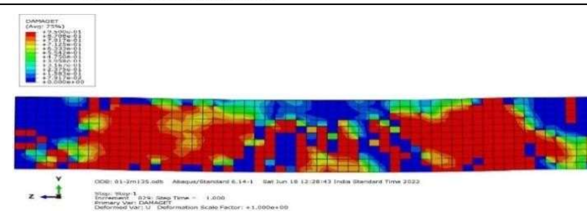
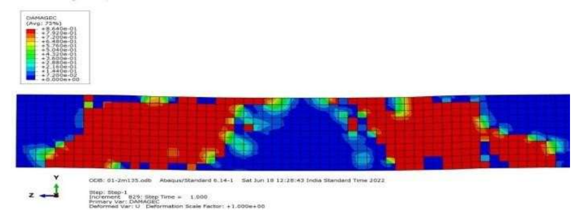
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
A-3M85			
A-R135			
A-1M135			
A-2M135			

Fig. 7.4 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of2.2

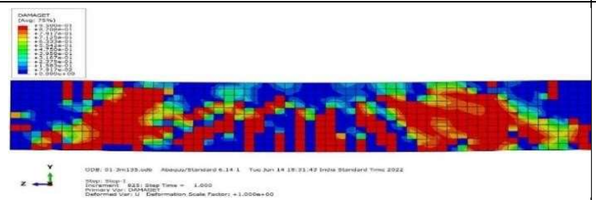
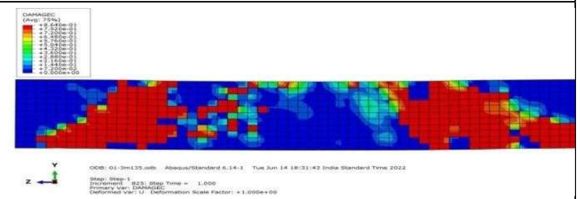
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
A-3M135			

Fig. 7.4 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of2.2

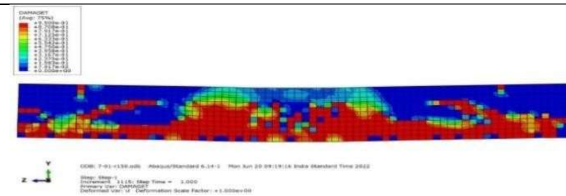
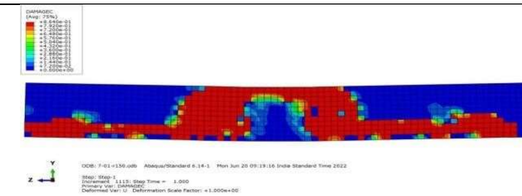
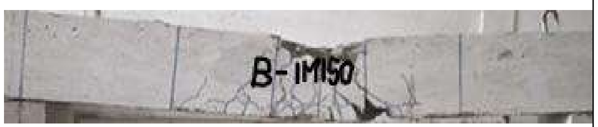
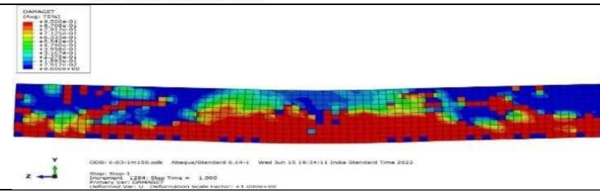
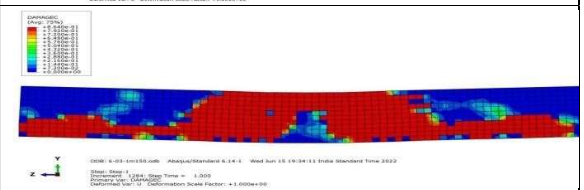
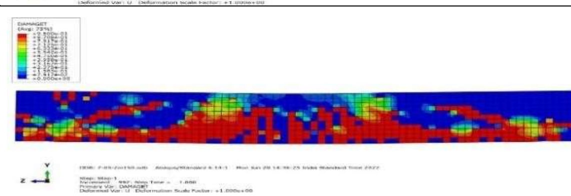
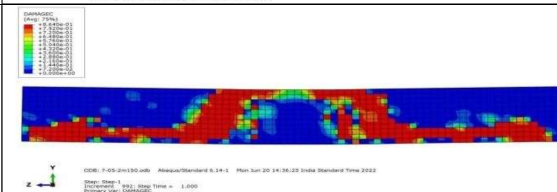
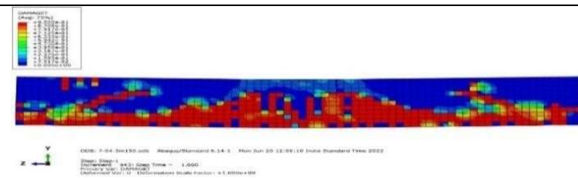
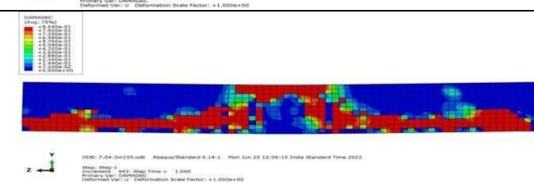
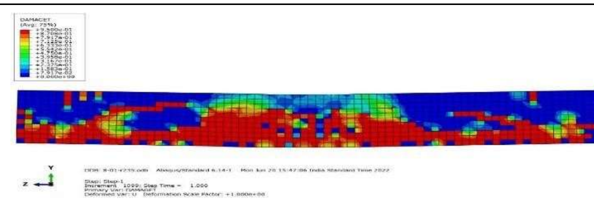
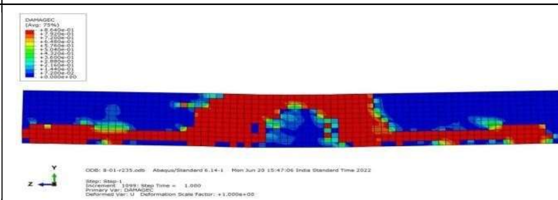
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
B-R150			
B-1M150			
B-2M150			
B-3M150			
B-R235			

Fig. 7.5 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of3

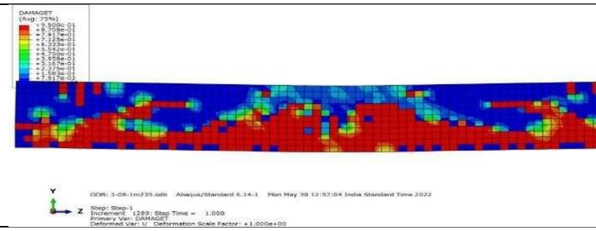
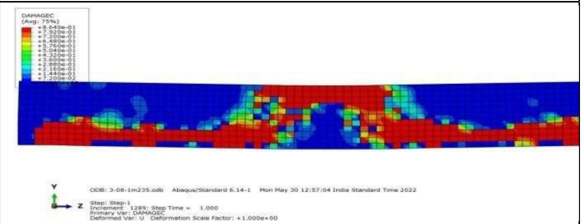
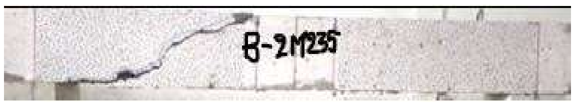
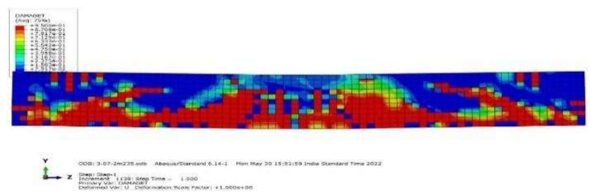
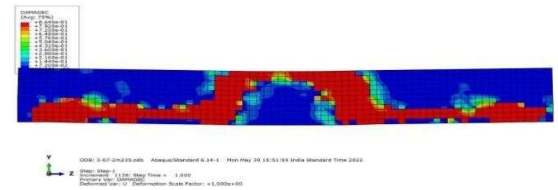
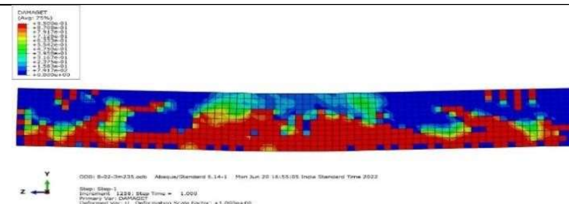
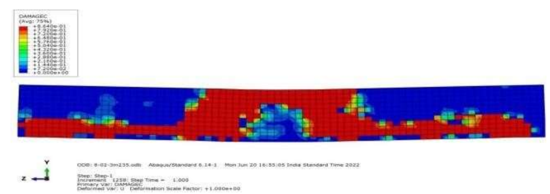
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
B-1M235			
B-2M235			
B-3M235			

Fig. 7.5 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of 3

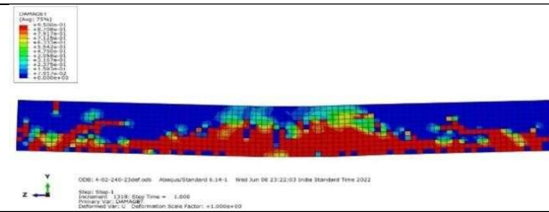
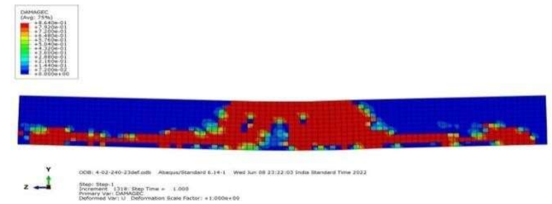
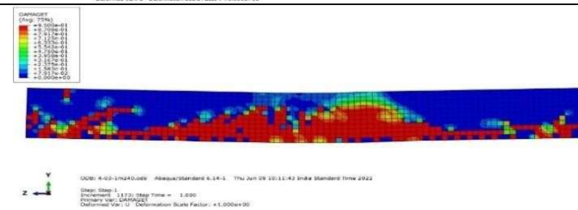
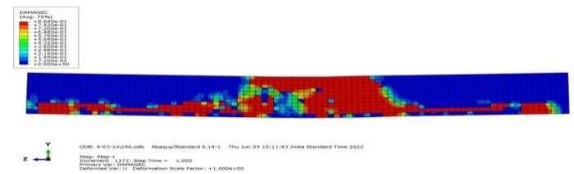
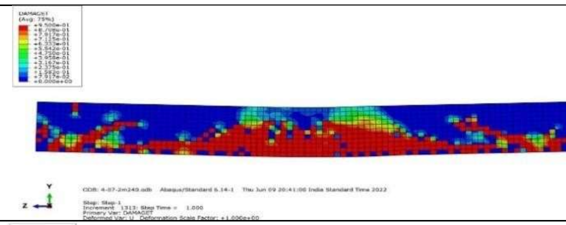
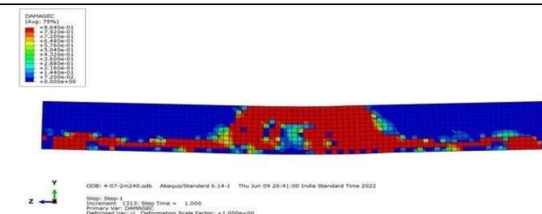
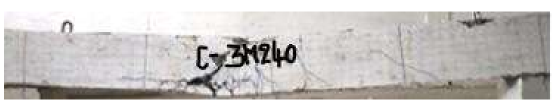
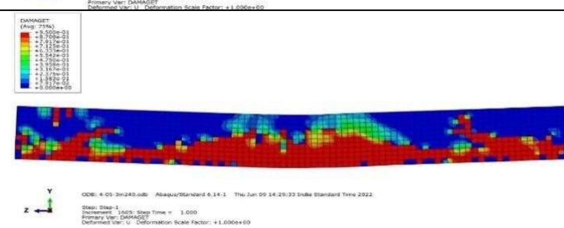
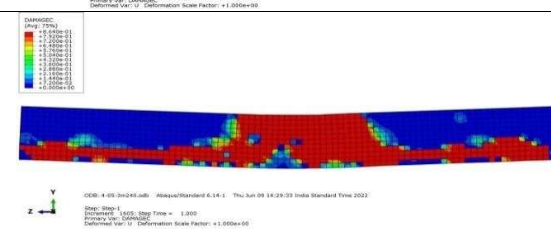
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
C-R240			
C-1M240			
C-2M240			
C-3M240			

Fig. 7.6 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of3.8

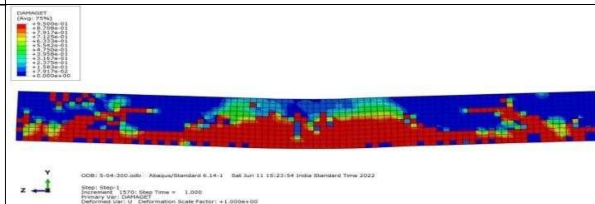
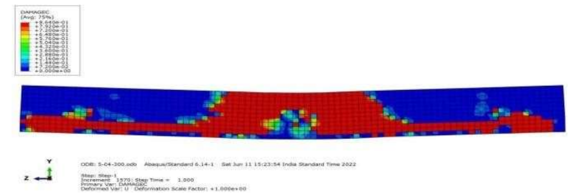
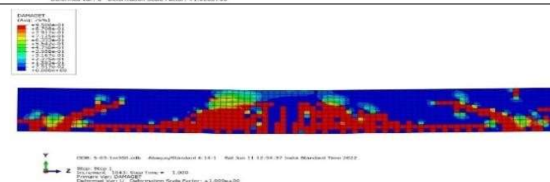
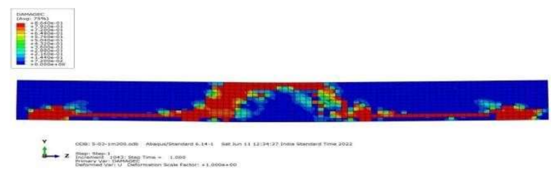
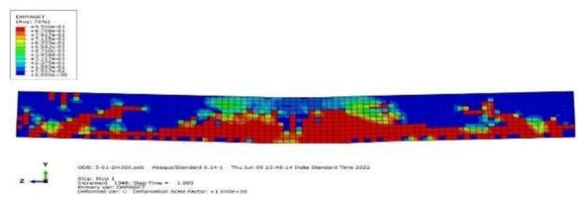
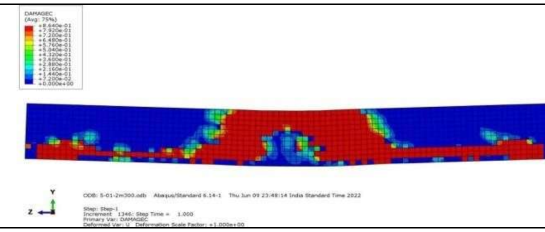
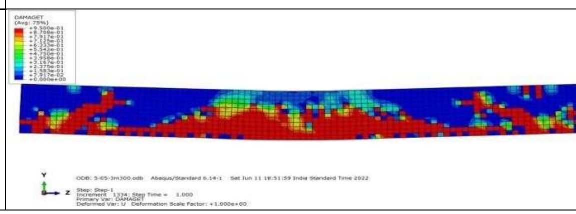
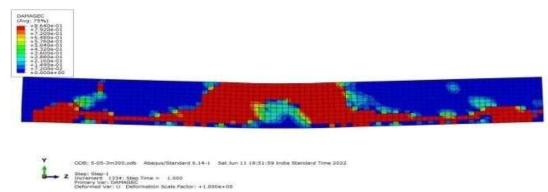
RC Beam	Experimental failure pattern	Damage Pattern in tension in ABAQUS	Damage Pattern in compression in ABAQUS
C-R300			
C-1M300			
C-2M300			
C-3M300			

Fig. 7.6 Phase-III experimental and numerical beams with tensile and compressive damage patterns for constant shear span to depth ratio of3.8

7.5.1 Load-Deflection Curves of Phase-III Beams:

From Phase-III experimental Program, three different a/d ratio with three different meshes results are taken from chapter 6 and numerical results of same beams considered from ABAQUS software are presented graphically in the form of load deflection curves and presented in three a/d ratios of 2.2, 3, 3.8 which indicates good correlation between them. In Load-Deflection curves, R/1M/2M/3M indicates conventional beams or type of welded wire mesh fallowed by spacing and representation of experimental(E)/ Numerical(A). Experimental results are presented in the form of dots and numerical as curve and observing these values, they are highly correlated. As numerical results are close to experimental results also proved the superior performance of welded wire mesh over the conventional beams and with the reduction of spacing which improves the load carrying capacity of the beams.

Load-deflection relation for each beam comparing both experimental and numerical results for a/d=2.2 is presented in fig.7.7

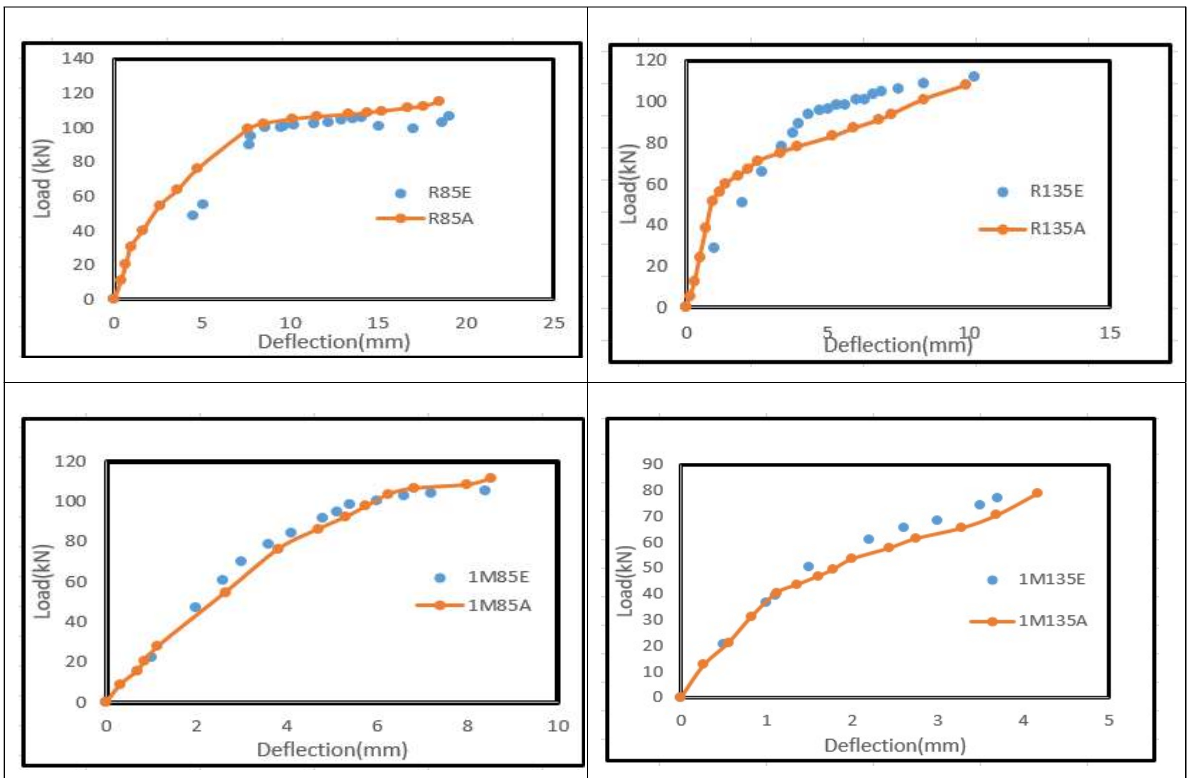


Fig 7.7 Comparative analysis of experimental and numerical beams for a/d=2.2

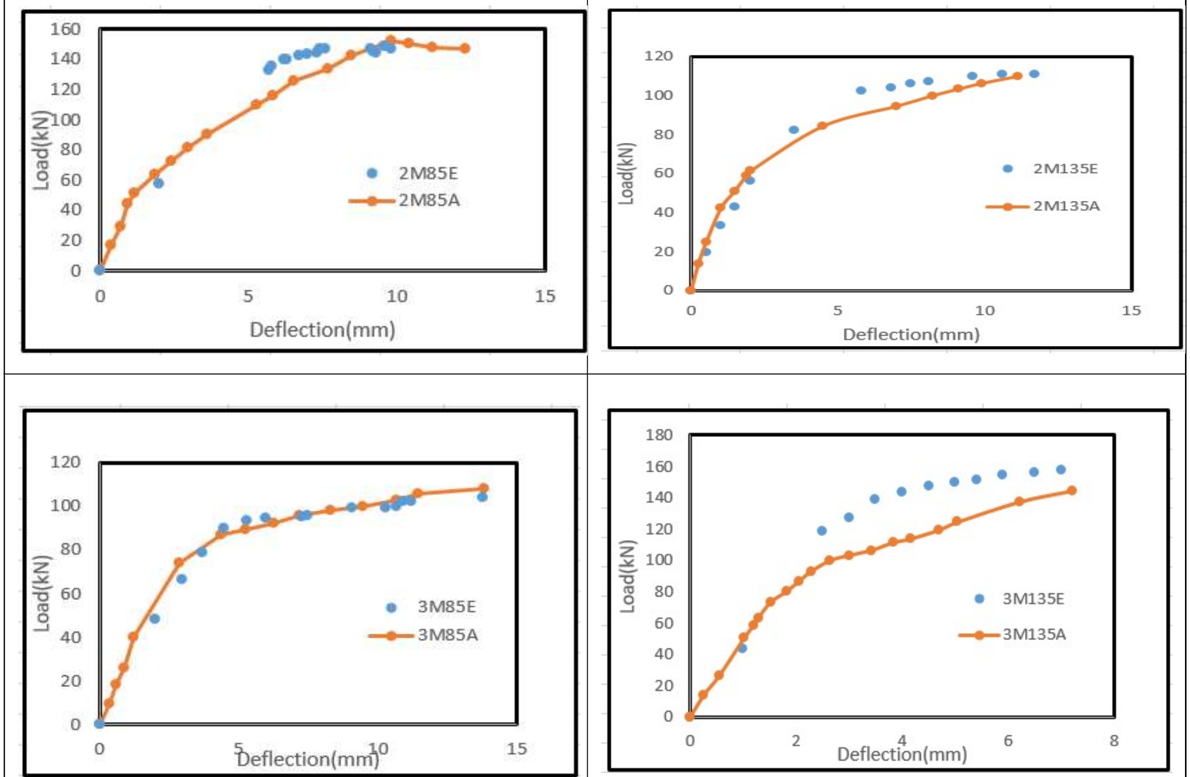


Fig 7.7 Comparative analysis of experimental and numerical beams for a/d=2.2

Comparison of numerical results of different meshes are presented for a/d =2.2 with spacing's of 85mm and 135mm shown in fig 7.8. For 85mm spacing beams 2M shows more load carrying capacity and for spacing of 135mm 3M shows more load carrying capacity.

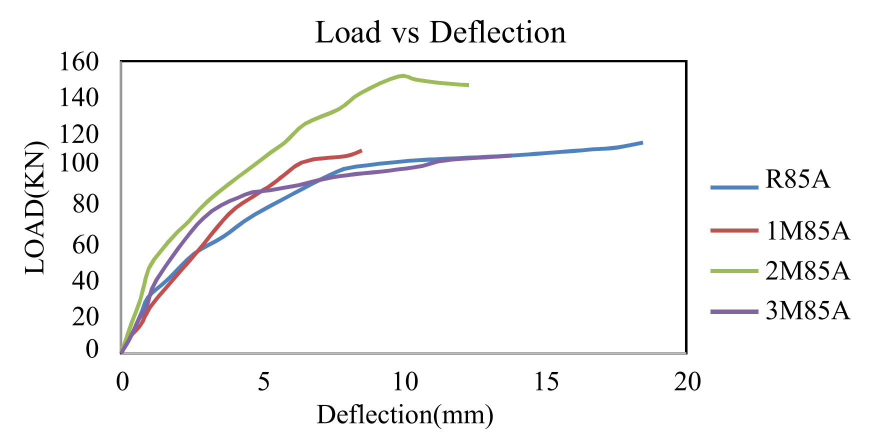


Fig. 7.8 Load deflection curves for different types of meshes fora/d=2.2

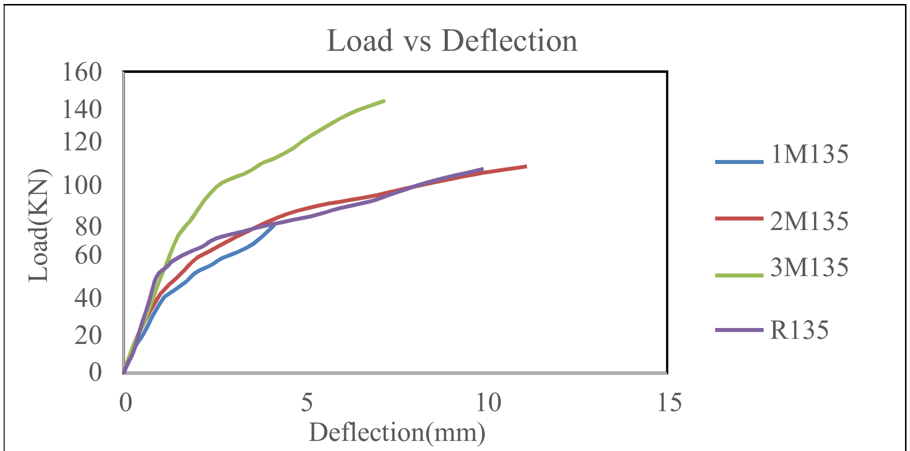


Fig. 7.8 Load deflection curves for different types of meshes for a/d=2.2

Load-deflection relation for each beam comparing both experimental and numerical results for a/d=3 is presented in fig.7.9

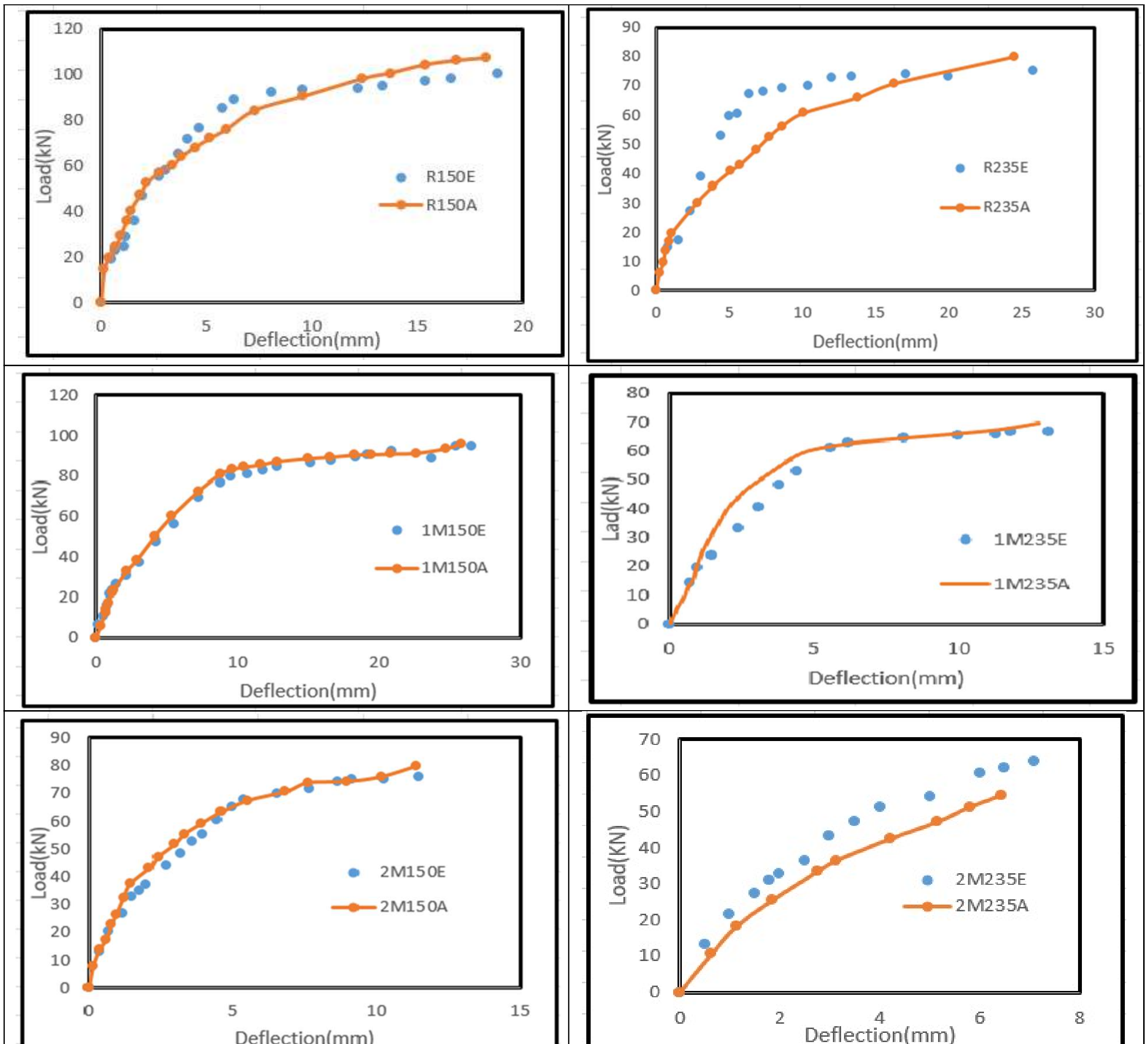


Fig 7.9 Comparative analysis of experimental and numerical beams for a/d=3

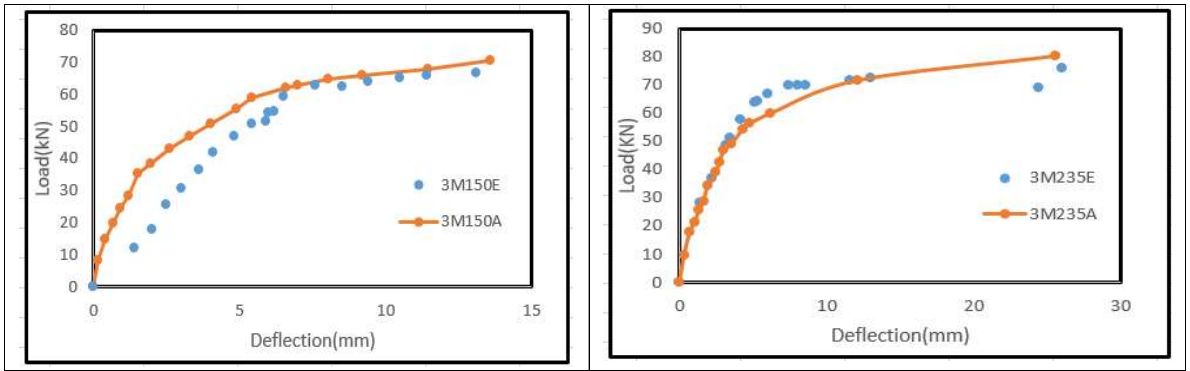


Fig 7.9 Comparative analysis of experimental and numerical beams for a/d=3

Comparison of numerical results of different meshes are presented for a/d =3 with spacings of 150mm and 235mm shown in fig 7.10. For 150mm spacing beams 1M presents higher load carrying capacity compared to other meshes but carrying almost equal load to that of conventional beam and for spacing of 235mm 3M presents higher load carrying capacity compared to other meshes but carrying almost equal load to that of conventional beam.

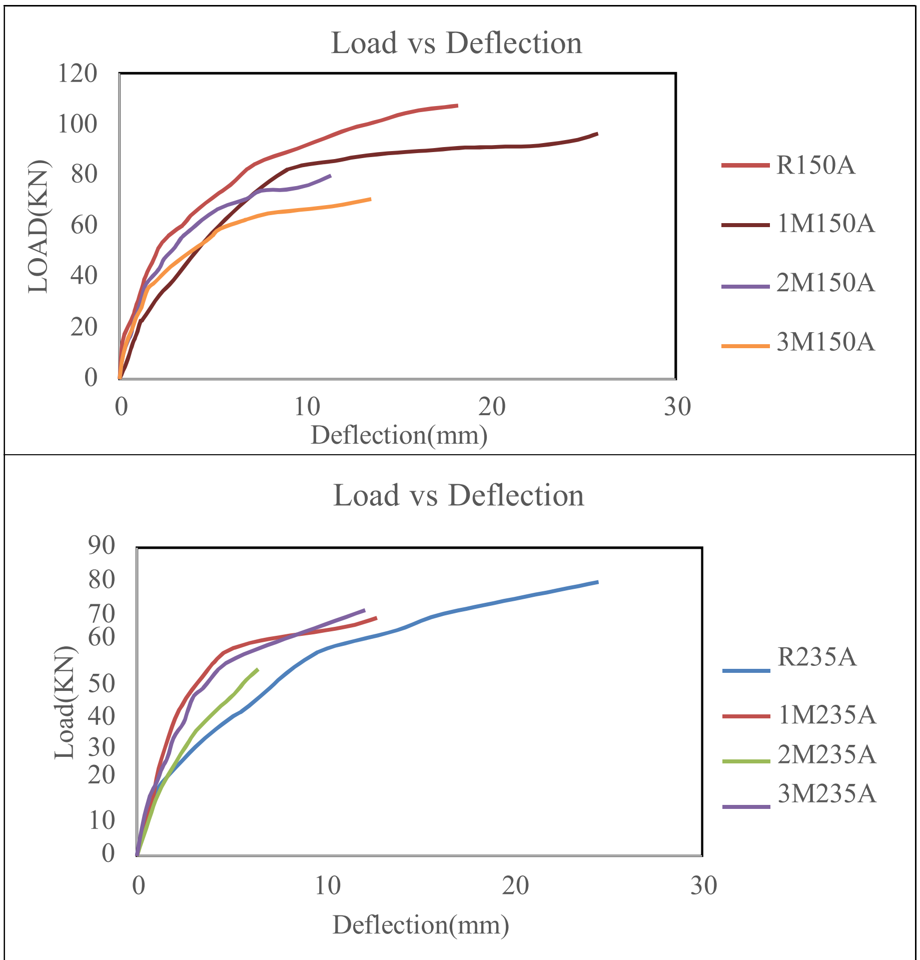


Fig. 7.10 Load deflection curves for different types of meshes for a/d=3

Load-deflection relation for each beam comparing both experimental and numerical results for a/d=3.8 is presented in fig.7.11

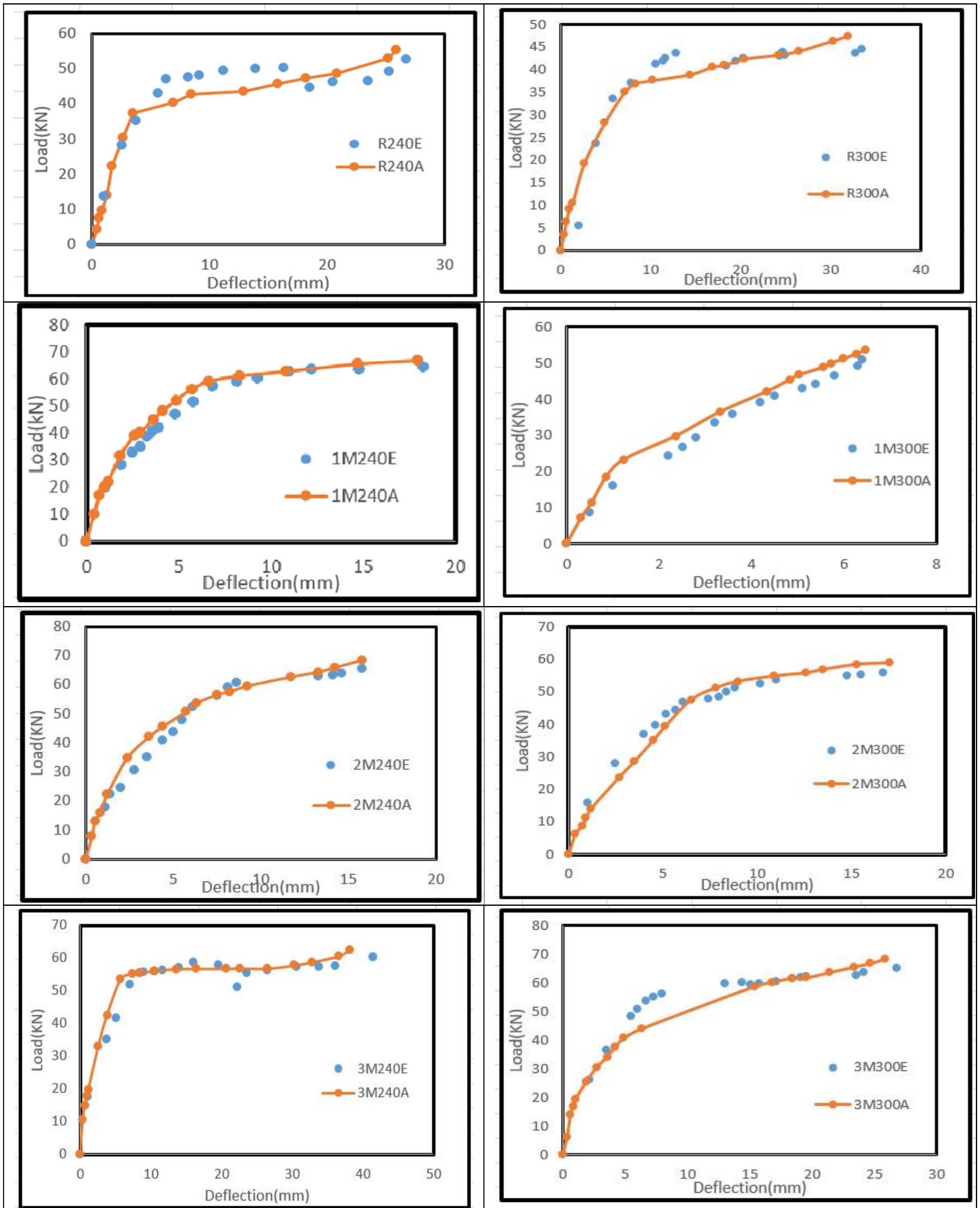
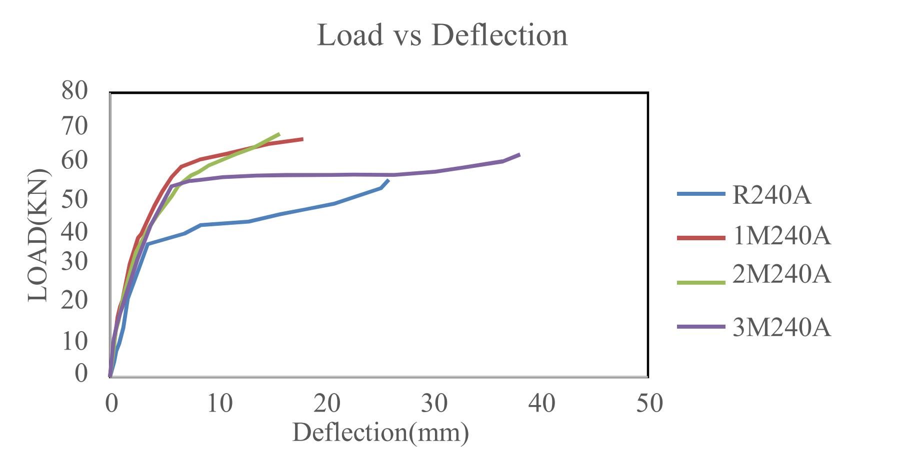


Fig 7.11 Comparative analysis of experimental and numerical beams for a/d=3.8

Comparison of numerical results of different meshes are presented for a/d =3.8 with spacing's of 240mm and 300mm shown in fig 7.12. For 240mm spacing beams 2M shows more load carrying capacity and for spacing of 300mm 3M shows more load carrying capacity.



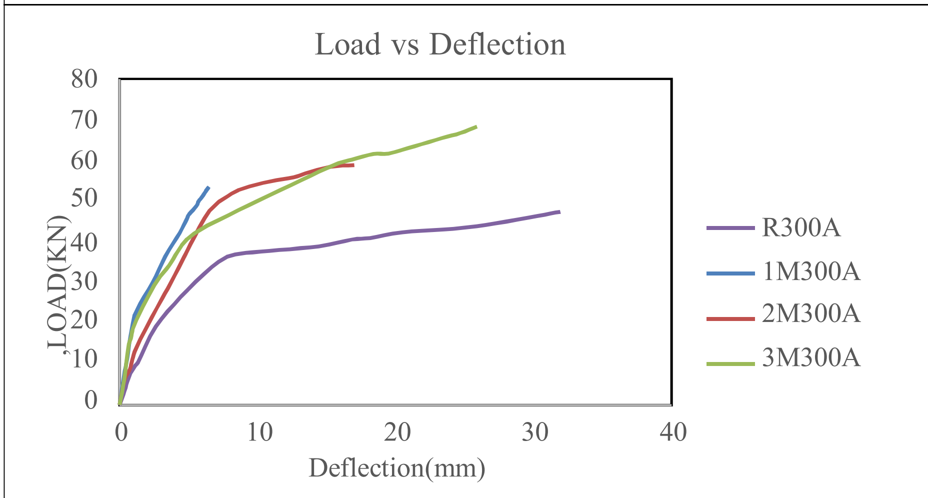


Fig. 7.12 Load deflection curves for different types of meshes for a/d=3.8

7.6 Parametric Study:

7.6.1 Effect of type of mesh to failure load:

The series of 24 beams for three shear span to effective depth ratios as 2.2, 3, 3.8 are presented combined representing its ultimate loads is presented in fig 7.13. This comparison indicates that performance of each mesh shows excellence at different spacings. In most of the cases 3M mesh beams carries more load compared to other beams fallowed 2M mesh beams but carried more or equal to conventional beams.

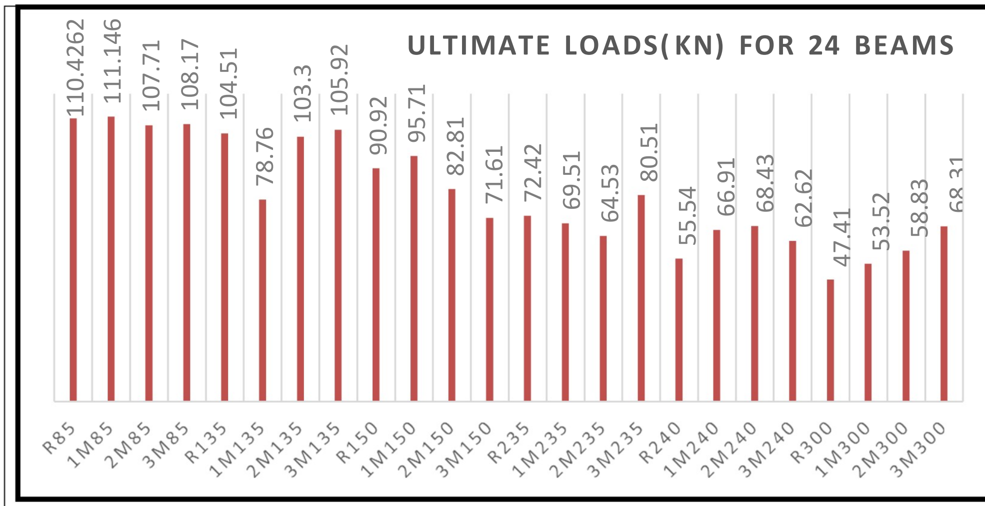


Fig 7.13 Representing numerical ultimate loads of all 24 beams

7.6.2 Effect of type of mesh to spacing of shear reinforcement

The performance of different meshes are compared for same spacing in Fig 7.14. Each mesh is indicated with different colour in the form of dot representation also compared with conventional beams. With the increase of spacing, 3M mesh performs better compared to other beams and even performed better in most of the spacings.

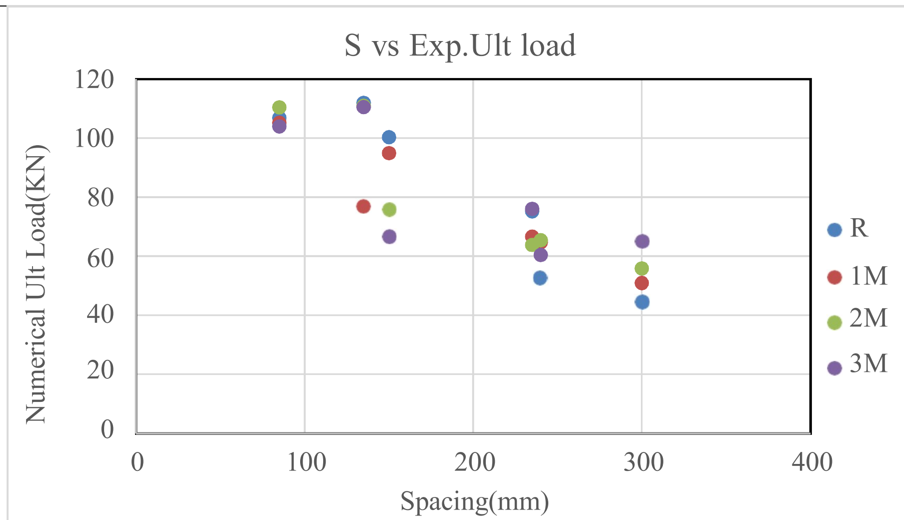


Fig 7.14 Comparison of ultimate loads of the all beam for particular spacing

7.7 Conclusions

1. The numerical model of RC beam provided with WWM as transverse reinforcement, simulated in ABAQUS FEA software estimated the ultimate loads and deflections that are in close agreement with the corresponding experimental values.
2. The percentage of error range between 1.01-14.52% were observed in the comparison of Numerical ultimate load with the experimental ultimate load. Except in some beam models, in most of the cases the ultimate load obtained from the Numerical model showed a higher value when compared to the experimental values.
3. A maximum percentage error of 15.9% was observed while comparing the deflection obtained through numerical models with that of the experimental values.
4. The crack patterns shown by the numerical models are nearly matching with the experimentally observed failure patterns.

Chapter 8

CONCLUSIONS

Chapter 8
CONCLUSIONS

8.1 General

In the present investigation, a study on the shear behavior of RC beam wherein the welded wire mesh is used as a core zone reinforcement is taken up with an objective to answer the following questions:

1. What is the efficacy of the core zone reinforcement in the form of Welded Wire Mesh (WWM) used either as transverse reinforcement replacing totally the use of conventional stirrups or as longitudinal core reinforcement apart from conventional rectangular stirrups, in improving the performance of RC beam in shear?
2. How to quantify the effect of using WWM as a transverse reinforcement replacing totally the use of conventional stirrups in RC beams with a fixed shear span to depth ratio?
3. What is the effect of WWM as a transverse reinforcement replacing totally the use of conventional stirrups on the behavior of RC beams with different shear span to depth ratios?
4. How the shear strength obtained through the numerical analysis of RC beams provided with welded wire mesh as shear reinforcement using ABAQUS compare with the experimental shear strength?

To answer the above questions, an experimental and analytical investigation was carried out in **FOUR** different phases. The following conclusions are made in different phases of the investigation carried.

Phase-I:

1. For the same spacing of stirrups as transverse reinforcement, the RC beam provided with welded wire mesh as longitudinal core zone reinforcement has shown not only increase in ultimate (failure) load but also changed the nature of failure from shear to flexure compared to that of the RC beams provided with only conventional stirrups.
2. The use of longitudinal core zone reinforcement provides shear resistance in continuous manner unlike the discrete resistance provided by the regular stirrups.
3. The continuity in resistance provided by the longitudinal core zone reinforcement against diagonal tension due to shear delays the formation of shear cracks and improves the performance of reinforced concrete members.

4. The increase in the consumption of the steel in using additional reinforcement in the form of welded wire mesh as a longitudinal core zone reinforcement can be compensated by reducing the number of stirrups by adopting the higher spacing of stirrups than required.
5. The use of welded wire mesh as longitudinal core zone reinforcement apart from reduced number of conventional stirrups did not violate the required serviceability norms.
6. In the case of RC beam provided with the longitudinal core zone reinforcement in place of conventional stirrups, enhanced the resistance at ultimate similar to that of conventional stirrups.
7. The RC beam with longitudinal core zone reinforcement apart from conventional stirrups has shown a greater number of smaller width cracks indicating enhanced ductility.
8. For the same spacing of transverse steel, the ultimate load of the RC beam with welded wire mesh as transverse reinforcement is more compared to the RC beams with conventional stirrups.
9. For the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM will be able to provide similar or better performance of RC beams compared to that of RC beams having conventional stirrups.
10. The nature of failure / behavior of the RC beam remained more or less similar with the replacement of conventional stirrups with welded wire mesh as transverse reinforcement for the same spacing of transverse steel in the form of mesh / stirrups.
11. As the spacing of transverse reinforcement (in the form of mesh / stirrups) reduced, the rate of increase of load in beams with weld mesh as core zone transverse reinforcement is observed to be more than that of beams with conventional stirrups
12. The increase in the ultimate loads together with satisfactory serviceability behavior and reduced consumption of transverse steel justifies the effectiveness of welded wire mesh as a transverse core zone reinforcement over the conventional stirrups.
13. For the same spacing of transverse reinforcement (in the form of mesh / stirrups) the weight of steel consumed in using the mesh as transverse core zone reinforcement is almost half of the weight of steel consumed in conventional stirrups for the same spacing leading to the economy in the steel quantity.
14. The use of mesh either as transverse reinforcement replacing the conventional stirrups or as longitudinal core zone reinforcement did not violate the required serviceability norms.
15. The behavior of the RC beams tested clearly indicates the superiority of the welded wire mesh either as transverse reinforcement replacing the conventional stirrups or as longitudinal core zone reinforcement from the point of performance at ultimate.

16. The welded wire mesh as a transverse core zone reinforcement is about 40% more effective compared to the WWM as longitudinal core zone reinforcement in improving the ultimate load capacity.

Phase-II:

1) The pattern of failure between the RC beams provided with WWM as a core zone transverse reinforcement and the RC beams provided with regular stirrups for the similar spacing of transverse steel is more or less similar.
2) For the similar spacing of transverse reinforcement, the quantity of transverse steel in the form of welded wire mesh of about 42 % of the stirrup area, is able to provide similar or better shear load capacity of RC beams compared to that of RC beams having conventional stirrups.
3) In RC beams provided with WWM as a core zone transverse reinforcement, the new parameter termed as 'Mesh index', which takes in to account the area ratio, distribution density and spacing ratio, can be used in estimating the shear strengths.
4) A factor 'K' accounting for the effect transverse core zone reinforcement in the form of WWM or stirrups can be related to the 'Mesh index (Mi)' using:

$$\mathbf{K = 0.539\ (Mi)^{0.287}}$$

5) A minimum area ratio of about 2.72 is required to have the beneficial effect of WWM over stirrups from the point enhancement in the shear strength.
6) The acceptable performance at service together with less consumption of transverse steel justifies the use of welded wire mesh over the conventional stirrups as transverse reinforcement for the similar spacing of transverse steel.

Phase-III:

1) The failure pattern of RC beams provided with welded wire mesh as transverse reinforcement is more or less similar to the RC beams provided with conventional stirrups for the same spacing of transverse steel irrespective of the a/d ratio.
2) For the similar spacing of transverse steel, even the less quantity of transverse steel in the form of WWM is able to provide similar or better ultimate load capacity of RC beams compared to that of RC beams having conventional stirrups irrespective of the a/d ratio.
3) The mesh index – a new parameter proposed which takes in to account the area ratio, distribution density and spacing ratio of the transverse reinforcement provided in the form of stirrups or WWM, can be used in estimating the ultimate loads with more accuracy in the case of RC beams with shear span to depth ratio greater than 2.5.

4) In all the RC beams tested irrespective of a/d ratio, the satisfactory serviceability behavior together with reduced consumption of transverse steel justifies the use of welded wire mesh over the conventional stirrups as transverse reinforcement for the same spacing of transverse steel.

Phase-IV:

1. The numerical model of RC beam provided with WWM as transverse reinforcement, simulated in ABAQUS FEA software estimated the ultimate loads and deflections that are in close agreement with the corresponding experimental values.
2. The percentage of error range between 1.01-14.52% were observed in the comparison of numerical ultimate load with the experimental ultimate load. Except in some beam models, in most of the cases the ultimate load obtained from the numerical model showed a higher value when compared to the experimental values.
3. A maximum percentage error of 15.9% was observed while comparing the deflection obtained through numerical models with that of the experimental values.
4. The crack patterns shown by the numerical models are nearly matching with the experimentally observed failure patterns.

8.2 Significant Contribution made:

1) The efficacy of the core zone reinforcement in the form of Welded Wire Mesh (WWM) used either as transverse reinforcement replacing totally the use of conventional stirrups or as longitudinal core reinforcement apart from conventional rectangular stirrups, in improving the performance of RC beam in shear, has been evaluated.
2) The effect of using WWM as a transverse reinforcement replacing totally the use of conventional stirrups in RC beams with a fixed shear span to depth ratio on shear strength has been quantified.
3) The effect of WWM as a transverse reinforcement replacing totally the use of conventional stirrups on the behavior of RC beams with different shear span to depth ratios, has been studied.
4) The numerical simulation of RC beams provided with welded wire mesh as shear reinforcement using ABAQUS is made and the analytical results are compared with the experimental shear strengths.

8.3 Scope for Future Investigation

With respect to the use of Welded wire mesh as a core zone reinforcement in RC beams, the following aspects requires further investigation.

- The efficacy of WWM as a core zone reinforcement in different grades of concrete.
- The Confinement and ductility aspect of WWM as a core zone reinforcement.
- This experimental program further extended to study the effect of horizontal wires and welding effect on the mesh index factor.
- Effect of WWM as a core zone reinforcement in RC beams with Self Compacting Concrete, Geopolymer Concrete, Fiber Reinforced concrete etc.,
- Rigorous Finite Element analysis like parametric study is need to be conducted for future investigation

PUBLICATIONS FROM THIS RESEARCH WORK

JOURNALS

1) Rama Seshu, D., Manjula, C., Rao, T.D.G. *et al.* A novel means of improving the performance of reinforced concrete beams using the welded wire mesh as core zone reinforcement. *Asian J Civ Eng* **21**, 959–965 (2020). **(Scopus) https://doi.org/10.1007/s42107-020-00252-0**

2) Rama Seshu, D., Manjula, C., Rao, T.D.G. *et al*. A novel method of using prefabricated weld mesh as longitudinal core reinforcement for resisting the shear in reinforced concrete beams. Journal of structural Engineering, 47 (4), 362-368 (2020) **(Scopus)**

3) Rama, S. D., Manjula. C., (2020). A new way of using welded wire mesh [WWM] for enhancing the shear strength in reinforced concrete beams. *Cement-Wapno-Beton= Cement Lime Concrete*, *25*(3). **(SCI). http://doi.org/10.32047/CWB.2020.25.3.3**

4) Rama Seshu, D., Manjula, C., Rao, T.D.G. *et al*. The weld coefficient - a new parameter accounting for shear resistance of welded wire mesh in place of conventional stirrups as shear reinforcement in RC beams. Journal of structural Engineering, 47(5), 440-449 (2021). **(Scopus)**

5) Seshu, D.R., Manjula, C., Rao, T.D.G. *et al.* An experimental study on the effect of the mesh index: a new parameter influencing the shear strength of RC beams provided with welded wire mesh as transverse reinforcement. *Asian J Civ Eng* 24, 1015–1025 (2023). **(Scopus). https://doi.org/10.1007/s42107-022-00550-9**

6) Ch, M., Rao, T. D. G., & Rao, C. B. K. (2023). A study on the behavior of RC beams provided with WWM as shear reinforcement for different shear span to depth ratios.

PATENT JOURNAL:

- An Indian Patent filed with a title “Prefabricated Mesh as Longitudinal Core Reinforcement in Reinforced Concrete Members”. (**Application No.202041003566 A** –Publication dt 07-02-2020- First Examination Report (FER) Completed).

BOOK CHAPTER

- Manjula, C., Rama Seshu, D., Gunneswara Rao, T.D. (2023). A Numerical Study on the Shear Strength of RC Beams Provided with Welded Wire Mesh as Core Zone Reinforcement. In: Vilventhan, A., Singh, S.B., Delhi, V.S.K. (eds) Advances in Construction Materials and Management. ACMM 2022. Lecture Notes in Civil Engineering, vol 346. Springer, Singapore. https://doi.org/10.1007/978-981-99-2552-0_39

INTERNATIONAL CONFERENCE PAPERS

- A Review paper titled 'An Appraisal on Shear Strength of Concrete for Different Codes', has been presented in the International Conference on "Innovative Trends in Civil Engineering for Sustainable Development (ITCSD - 2019)", held at NIT Warangal, during September 13-15th,2019.

NATIONAL CONFERENCE PAPERS

- A Paper titled 'A Numerical study on the shear strength of RC beams provided with welded wire mesh as core zone reinforcement' has been presented in the national conference on "Advances in Construction Materials & Management (ACMM-2022)", held at NIT Warangal, during December 16-17th, 2022.

References

Alhoubi, Y., Tabsh, S.W. and Younes, A., 2023. Use of Welded Wire Reinforcement as Lateral Reinforcement in Concrete Beams: Part 1--Shear. ACI Structural Journal, 120(3).

Abadel, A. A. (2021). Experimental investigation for shear strengthening of reinforced self-compacting concrete beams using different strengthening schemes. Journal of Materials Research and Technology, 15, 1815-1829.

Al-Rousan, R.Z., 2021. The behavior of heated damaged shear-deficient RC beams reinforced internally with welded wire mesh. Case Studies in Construction Materials, 15, p.e00687.

Al Nuaimi, N., Sohail, M. G., Hawileh, R. A., Abdalla, J. A., & Douier, K. (2020).Durability of reinforced concrete beams strengthened by galvanized steel mesh-epoxy systems under harsh environmental conditions. *Composite Structures*, *249*, 112547.

Albidah, A., Abadel, A., Abbas, H., Almusallam, T., & Al-Salloum, Y. (2019). Experimental and analytical study of strengthening schemes for shear deficient RC deepbeams. *Construction and building materials*, *216*, 673-686.

Alexander, D., & Ramakrishnan, S. (2016). Design of RC beam with and without weldedmesh as shear reinforcement in flexural and shear behaviour. *International Journal of Advanced Engineering Research and Technology (IJAERT)*, *4*(6), 2348-8190.

Al-Nasra, M. M., & Asha, N. M. (2013). Shear failure investigation of reinforced concrete beams with swimmer bars. Journal of Civil Engineering and Construction technology, 4(2), 56-74.

Alyousif, A., Anil, O., Sahmaran, M., Lachemi, M., Yildirim, G., & Ashour, A. F. (2016). Comparison of shear behaviour of engineered cementitious composite and normal concrete beams with different shear span lengths. Magazine of Concrete Research, 68(5), 217-228.

Amorn, W., Bowers, J., Girgis, A., & Tadros, M. K. (2007). Fatigue of deformed welded- wire reinforcement. *PCI journal*, *52*(1), 106.

Arslan, G., & Polat, Z. (2013). Contribution of concrete to shear strength of RC beams failing in shear. *Journal of Civil Engineering and Management*, *19*(3), 400-408.

Ayyub, B. M., Al-Mutairi, N., & Chang, P. (1994). Bond strength of welded wire fabric in concrete bridge decks. *Journal of Structural Engineering*, *120*(8), 2520-2531.

Ayyub, B. M., Al-Mutairi, N., & Chang, P. (1994). Splicing strength of welded steel mesh in concrete bridge decks. *Journal of Structural Engineering*, *120*(8), 2532-2546.

AYYUB, B., CHANG, P., & AL-MUTAIRI, N. A. (1994). Welded wire fabric for bridges. I. Ultimate strength and ductility. II. Fatigue strength. *Journal of structural engineering(New York, NY)*, *120*(6), 1892-1966.

Baghi, H., & Barros, J. A. (2018). Design-oriented approach to predict shear strength of reinforced concrete beams. *Structural Concrete*, *19*(1), 98-115.

BIS, I. (2000). 456 (2000) Plain and reinforced concrete-Code of Practice. *Bureau of Indian Standards, New Delhi, India*.

Bischoff, P. H., Valsangkar, A. J., & Irving, J. (2003). Use of fibers and welded-wire reinforcement in construction of slabs on ground. *Practice periodical on structural design and construction*, *8*(1), 41-46.

British Standard, B. S. (1997). 8110,". *The Structural Use of Concrete." British Standard Institution*.

Canadian Standards Association. (2004). *Design of concrete structures*. Mississauga, Ont.: Canadian Standards Association.

Carmona, J. R., & Ruiz, G. (2014). Bond and size effects on the shear capacity of RC beams without stirrups. *Engineering Structures*, *66*, 45-56.

Chen, H., Yi, W. J., & Hwang, H. J. (2018). Cracking strut-and-tie model for shear strength evaluation of reinforced concrete deep beams. *Engineering Structures*, *163*, 396-408.

Cladera, A., & Mari, A. R. (2004). Shear design procedure for reinforced normal and high-strength concrete beams using artificial neural networks. Part II: beams with stirrups. *Engineering structures*, *26*(7), 927-936.

Cladera, A., & Marí, A. R. (2004). Shear design procedure for reinforced normal and high-strength concrete beams using artificial neural networks. Part I: beams without stirrups. *Engineering structures*, *26*(7), 917-926.

Cladera, A., & Mari, A. R. (2005). Experimental study on high-strength concrete beams failing in shear. *Engineering Structures*, *27*(10), 1519-1527.

CODE, ACI. (2014). 318-14: Building Code Requirements for Structural Concrete and Commentary. *American Concrete Institute: Farmington Hills, MI, USA*.

Code, M. (2010). fib model Code for concrete structures. *Structural Concrete*, *14*.

Cui, M., Nie, X., Fan, J., Li, S., Liufu, J., & Huang, Z. (2019). Experimental study on theshear performance of RC beams reinforced with welded reinforcement grids. *Construction and Building Materials*, *203*, 377-391.

Demir, A., Caglar, N., & Ozturk, H. (2019). Parameters affecting diagonal cracking behavior of reinforced concrete deep beams. *Engineering Structures*, *184*, 217-231.

Earij, A., Alfano, G., Cashell, K., & Zhou, X. (2017). Nonlinear three–dimensional finite– element modelling of reinforced–concrete beams: Computational challenges andexperimental validation. *Engineering Failure Analysis*, *82*, 92-115.

El-Sayed, T. A., & Erfan, A. M. (2018). Improving shear strength of beams using ferrocement composite. *Construction and Building Materials*, *172*, 608-617.

Européen, Code. (2004). Eurocode 2: Design of concrete structures—part 1-1: General rules and rules for buildings. *London: British Standard Institution*.

Farahmandpour, C., Dartois, S., Quiertant, M., Berthaud, Y., & Dumontet, H. (2017). A concrete damage–plasticity model for FRP confined columns. *Materials and Structures*, *50*, 1-17.

Gandomi, A. H., Mohammadzadeh, D., Pérez-Ordóñez, J. L., & Alavi, A. H. (2014). Linear genetic programming for shear strength prediction of reinforced concrete beams withoutstirrups. *Applied Soft Computing*, *19*, 112-120.

Gayathri, S., & Kirthiga, T. (2018). Experimental and analytical investigation of RC beam with welded wire mesh as shear reinforcement. *Int. Res. J. Eng. Technol*, *5*, 2078-2081.

Gedik, Y. H., Nakamura, H., Ueda, N., & Kunieda, M. (2011). A new stirrup design considering 3-D effects in short deep beams. *Procedia engineering*, *14*, 2964-2971.

Genikomsou, A. S., & Polak, M. A. (2015). Finite element analysis of punching shear ofconcrete slabs using damaged plasticity model in ABAQUS. *Engineering structures*, *98*, 38-48

Ghahremannejad, M., & Abolmaali, A. (2018). Prediction of shear strength of reinforcedconcrete beams using displacement control finite element analysis. *Engineering Structures*, *169*, 226-237.

Ghiassi, B., & Soltani, M. (2010). Local stress field approach for shear failure assessment of reinforced concrete members. *Journal of Advanced Concrete Technology*, *8*(2), 223-238.

Grassl, P., Xenos, D., Nyström, U., Rempling, R., & Gylltoft, K. (2013). CDPM2: A damage-plasticity approach to modelling the failure of concrete. *International Journal of Solids and Structures*, *50*(24), 3805-3816

Gunawan, D., Okubo, K., Nakamura, T., & Niwa, J. (2020). Shear capacity of RC beamsbased on beam and arch actions. *Journal of Advanced Concrete Technology*, *18*(5), 241- 255.

Hadi, M. N., & Zhao, H. (2011). Experimental study of high-strength concrete columns confined with different types of mesh under eccentric and concentric loads. *Journal ofmaterials in civil engineering*, *23*(6), 823-832.

Hany, N. F., Hantouche, E. G., & Harajli, M. H. (2016). Finite element modeling of FRP-confined concrete using modified concrete damaged plasticity. *Engineering Structures*, *125*, 1-14.

Hong, S. G., & Ha, T. (2012). Effective Capacity of Diagonal Strut for Shear Strength of Reinforced Concrete Beams without Shear Reinforcement. *ACI Structural Journal*, *109*(2).

Hu, B., & Wu, Y. F. (2017). Quantification of shear cracking in reinforced concrete beams. *Engineering Structures*, *147*, 666-678.

Hu, B., & Wu, Y. F. (2018). Effect of shear span-to-depth ratio on shear strength components of RC beams. *Engineering Structures*, *168*, 770-783.

Huang, Z., Tu, Y., Meng, S., Bagge, N., Nilimaa, J., & Blanksvärd, T. (2019). Validation of a numerical method for predicting shear deformation of reinforced concretebeams. *Engineering Structures*, *197*, 109367.

Hunegnaw, C. B., & Aure, T. W. (2021). Effect of orientation of stirrups in combination with shear span to depth ratio on shear capacity of RC beams. *Heliyon*, *7*(10).

Ibrahim, H. M. (2011). Experimental investigation of ultimate capacity of wired mesh- reinforced cementitious slabs. *Construction and Building Materials*, *25*(1), 251-259.

Jeong, J. P., & Kim, W. (2014). Shear resistant mechanism into base components: Beamaction and arch action in shear-critical RC members. *International Journal of Concrete Structures and Materials*, *8*, 1-14.

Kani, G. N. J. (1964, April). The riddle of shear failure and its solution. In *Journal Proceedings* (Vol. 61, No. 4, pp. 441-468).

Kim, H. G., Jeong, C. Y., Kim, M. J., Lee, Y. J., Park, J. H., & Kim, K. H. (2018). Predictionof shear strength of reinforced concrete beams without shear reinforcement considering bond action of longitudinal reinforcements. *Advances in Structural Engineering*, *21*(1), 30- 45.

Kuo, W. W., Cheng, T. J., & Hwang, S. J. (2010). Force transfer mechanism and shear strength of reinforced concrete beams. *Engineering Structures*, *32*(6), 1537-1546.

Lee, S. H., Abolmaali, A., Shin, K. J., & Lee, H. D. (2020). ABAQUS modelling for post-tensioned reinforced concrete beams. *Journal of Building Engineering*, *30*, 101273.

Li, W., & Leung, C. K. (2016). Shear span–depth ratio effect on behavior of RC beam shear strengthened with full-wrapping FRP strip. *Journal of Composites for Construction*, *20*(3), 04015067.

Liu, J., & Mihaylov, B. I. (2016). A comparative study of models for shear strength of reinforced concrete deep beams. *Engineering Structures*, *112*, 81-89.

Mansour, M. Y., Dicleli, M. U. R. A. T., Lee, J. Y., & Zhang, J. J. E. S. (2004). Predicting the shear strength of reinforced concrete beams using artificial neural networks. *Engineering Structures*, *26*(6), 781-799.

Mansuri. A., Patel. ch., Patel. M., Tank. T., and Vasanwala. S A.,(2017). Behaviour of Strengthened RC beams in shear, International Journal of Engineering Development and Research IJEDR, 5(6), 417-423.

Megarsa, E., & Kenea, G. (2022). Numerical investigation on shear performance of reinforced concrete beam by using ferrocement composite. *Mathematical Problems inEngineering*, *2022*.

Minh, H. L., Khatir, S., Wahab, M. A., & Cuong-Le, T. (2021). A concrete damage plasticity model for predicting the effects of compressive high-strength concrete under static and dynamic loads. *Journal of Building Engineering*, *44*, 103239.

Mohamed, H. A. (2017). Effect of using swimmer bars on the behavior of normal and high strength reinforced concrete beams. *Ain Shams Engineering Journal*, *8*(1), 29-37.

Rebeiz, K. S., Fente, J., & Frabizzio, M. A. (2001). Effect of variables on shear strength of concrete beams. *Journal of materials in civil engineering*, *13*(6), 467-470.

Rewers, I. (2019, February). Numerical analysis of RC beam with high strength steel reinforcement using CDP model. In *IOP Conference Series: Materials Science andEngineering* (Vol. 471, No. 2, p. 022025). IOP Publishing.

Shaaban, I. G., Shaheen, Y. B., Elsayed, E. L., Kamal, O. A., & Adesina, P. A. (2018).Flexural characteristics of lightweight ferrocement beams with various types of core materials and mesh reinforcement. *Construction and Building materials*, *171*, 802-816.

Shatarat, N., Katkhuda, H., & Alqam, M. (2016). Experimental investigation of reinforced concrete beams with spiral reinforcement in shear. *Construction and Building Materials*, *125*, 585-594.

Shuraim, A. B. (2014). A novel approach for evaluating the concrete shear strength in reinforced concrete beams. *Latin American Journal of Solids and Structures*, *11*, 93-112.

Słowik, M. (2014). Shear failure mechanism in concrete beams. *Procedia materials science*, *3*, 1977-1982.

Somraj, A., Fujikake, K., & Li, B. (2013). Influence of loading rate on shear capacity of reinforced concrete beams. *International Journal of Protective Structures*, *4*(4), 521-543.

Subramanian, N. (2003). Shear strength of high strength concrete beams: Review of codal provisions. *Indian Concrete Journal*, *77*(5), 1090-1094.

Tabsh, S. W. (2007). Stress-strain model for high-strength concrete confined by welded wire fabric. *Journal of materials in civil engineering*, *19*(4), 286-294.

Varney, J. C., Brown, M. D., Bayrak, O., & Poston, R. W. (2011). Effect of Stirrup Anchorage on Shear Strength of Reinforced Concrete Beams. ACI Structural Journal, 108(4).

Wu, Y. F., & Hu, B. (2017). Shear strength components in reinforced concrete members. *Journal of Structural Engineering*, *143*(9), 04017092.

Xiao Ti Xuan. (1987). Effectiveness of welded wire fabric as shear reinforcement in pretensioned prestressed concrete T-beams. Masters Thesis, University of Manitoba, Winnpeg, Canada

Yoo, M. (2022). Experimental Study on the Shear Strength of Reinforced Concrete Beams with Various Integrated Shear Reinforcements. *Materials*, *15*(9), 3091.

Zhang, J. H., Li, S. S., Xie, W., & Guo, Y. D. (2020). Experimental study on shear capacity of high strength reinforcement concrete deep beams with small shear span–depthratio. *Materials*, *13*(5), 1218.

Zhao, P., Xu, G., Wang, Q., Zhao, J., & Liu, X. (2018). Influence of stirrup arrangementson the corrosion characteristics of reinforced concrete members. *Construction and Building Materials*, *192*, 683-695.

Zhou, L., & Wan, S. (2022). Shear behavior of UHPC beams with small shear span to depth ratios based on MSTM. *Case Studies in Construction Materials*, *16*, e01134.