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Comparative Evaluation of Finite Element Models and Types of Analyses for a Bolted Joint

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The present work is aimed at evaluating different ways in which a given joint can be analyzed using the Finite Element Method. The bolt is modeled using line elements (link) or area elements (continuum) and a comparative evaluation is carried out. Each of these types is further subdivided into three categories viz., plane stress, axisymmetric, and three-dimensional models. Thus a total of six models are proposed to be analyzed and compared. As the bolt shares only a small fraction of external load in a well-tightened joint, the relative flexibility of a bracket is also studied as an example in the present work. Comparing the results of these analyses it was found that the type of model used for the bolt is more important than the type of analysis. This aspect is probed further to find the essential difference between bolt as link and bolt as continuum. The analysis is carried out using ANSYS, which enables writing many parametric programs.
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1 Introduction

Bolted connections are the oldest method used for connecting two components together for their ease of joining and separation and behave as a single unit as long as sufficient compressive pressure exists at the interface or sufficient tension exists in the bolt. External load on the joint cause reduction in interface pressure and creep occurring at elevated temperature reduces the tensile load in the bolt and thus the strength of the bolted joint.

Three-dimensional Finite Element models, which realistically simulate bolted joint behavior, have been developed by Highen and Grimm [1] to understand the working of a bolted joint. Webjorn [2] developed the theoretical background to the Verax compact flange system. It is proved by Rotscher [3] that only a minor part of the external loads adds to the bolt preload but not the complete load as assumed. Wileman et al. [4] developed a method for computation of member stiffness in bolted connections. Gould and Mikic [5] computed the pressure distribution in the contact zones and the radii at which plates will be separated by the FE methods and also using experimental methods. The design guidelines presented by William [6] ensures that the highest preload, which can be applied, after considering the effects such as frictional scatter used as the basis of the product design. Hwang and Stalling [7] have performed the analysis on the connection of a fuel duct of a rocket engine, as this is a typical application for a bolted flange connection in aero space structure. Hanzheng et al. [8] performed the analysis in which the bolt load was applied via an extremely stiff washer to eliminate the effect of bolt head deflection on the results.

Comparing all the possible ways that are available for modeling the bolted joints, analysis is proposed to be carried out by evaluating six different ways of modeling. They are representations of bolt by link or continuum; each in turn is modeled using three different approaches viz., 2D, 3D, and axisymmetrcal models, using compression only springs along the interface, which provides the possibility of separation at the interface.

2 General Methods of Tightening the Bolts

Pretension is an important aspect of any bolted connection and initial tightening is imposed in general by a torque wrench or by physically stretching the bolt, where an axial load is imposed on the bolt. The tightening torque is equal to the product of the force applied to the wrench end and the wrench arm. It produces axial force stretching the bolt and overcoming the moment of friction in the threads and on the nut-bearing surface. Axial load due to stretching can be developed through mechanical or thermal means. In both of these methods the bolt is first stretched by applying a force or by heating the bolt. Once the bolt elongates, a nut is tightened with the hand. After cooling or removal of the applied force, the bolt tries to retain its natural position, which is opposed by the plate underneath. This produces compression in

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Table 1 Dimensions of the components

Component	Dimensions (mm)
Bolt diameter	35
Flange height	70
Flange length	140
Washer diameter	70
Pitch	70
Nut height	17.5

Table 3 $P=640$ KN, $A=962.11$ mm^2, stress in the bolt$=P/A$ $=665.204$ N/mm^2, initial strain$=665.204/E=0.003168$.

Bolt model	Type of analysis	Remaining bolt tension (KN)
Link	Plane stress	538.78
Link	Axisymmetric	581
Link	Three-D	599.28
Continuum	Plane stress	465.42
Continuum	Axisymmetric	464.72
Continuum	Three-D	465.23

the plate and tension in the bolt. There is a basic difference in these approaches of introducing bolt pretension. It is known that the bolt pretension causes compression in the parts joined together. Hence the applied pretension is always less than the retained pretension and the difference is attributed to compression in the plate. In case of the bolt stretching method the retained tension is less than the applied tension. In the case of the torque tightening method the plate compression is accounted for and the torque meter reads accordingly. Thus Finite Element modeling should properly account for the method of tightening specified.

3 Finite Element Analysis of Bolted Joints

The aim of the present work is to carry out comparative evaluation of two ways of modeling a bolt (line elements, "link" or area elements, "continuum"). Each of these types is further subdivided into three categories: plane stress, axisymmetric, and three-dimensional models. A total of six models are prepared to be compared and analysis is carried out for plates joined together by means of a centrally placed bolt considering a clear shank and has threads only in the end, where a nut is tightened (Table 1). The plate and one-quarter of the bolt is modeled (Fig. 1). For the link model, the material properties used are same for both the bolt and the clamped parts (Table 2). The main aim of this analysis is to find the remaining bolt pretension and the compressive stress distribution at the parting plane. To simulate the bolt pretension for an axial load of 640 kN the initial stress is calculated. The area considered to be properly distributed where the middle nodes represent the full area and the corner nodes represent the half area. The initial strain is obtained as given below.

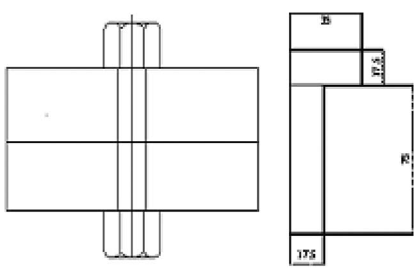

Fig. 1 Models of plate and bolt

Table 2 Material properties of bolt and clamped part

	Ansys variable		Value	
Material property	Bolt	Clamped parts	Bolt	Clamped parts
Coefficient of thermal expansion	ALPX	ALPX	0.12 E−06 MPa	0
Young's Modulus	EX	EX	0.21 E+05 MPa	0.21 E+05 MPa
Poisson ratio	NUXY	NUXY	0.3	0.3

For an explicit model in which the bolt is modeled as a continuum, the bolt pretension is simulated through a temperature change calculated. The value used in this analysis the temperature is equal to $-264°$C and is applied to the nodes of the model to obtain the remaining bolt pretension and the compressive stress along the interface of the clamped parts. When the bolt is modeled as a link, the bolt pretension simulated by giving an initial strain and when the bolt is modeled as a continuum the pretension is simulated by giving negative temperature to the nodes representing the bolt. Consolidated results of these analyses show the variation of compressive pressure (Table 3) along the interface for all the six analyses.

3.1 Effect of Plate Flexibility. The flexibility of the fastener and the fastened play an important role in the mechanics of bolted joints. Hence, an analysis is carried out to observe the effect of relative flexibilities by changing the value of Young's Modulus of the material for the plate and the results of the remaining bolt tension are presented for the bolt as a link and the bolt as a continuum (Table 4).

3.2 Bolt as Link and Bolt as Continuum. For these analyses a two-dimensional approach is followed and the bolt is modeled as a link and a continuum. The first analysis is carried out to see the effect of these two types of bolt models on the stiffness of the bolt.

In these models [Fig. 2(*a*)] CD represents ground, and AB represents the face of the bolt, which is in contact with the ground. This contact is presented by compression only springs. The bolt is pulled against the ground by applying external force P. It is found that the extension as seen in links model is 0.42×10^{-3} and that in continuum model is 0.451×10^{-3}. Thus the bolt represented by link is about 6% stiffer.

The other aspect that needs to be investigated is the nature of the transfer of load at the CD, which was taken as a ground in the earlier analysis. But in reality, the bolt presses another elastic medium and its elasticity is important. The ground is now shifted to EF [Fig. 2(*b*)] and the spar elements are introduced between CD (bolt) and EF (ground). Stiffness of these elements is in-

Table 4 Remaining bolt tension in the link and continuum models

	Plane stress, kN		Axisymmetric, kN		Three-dimensional, kN	
Young's Modulus	Link model	Continuum	Link model	Continuum	Link model	Continuum
2.1 E 3	44.491	39.19	55.420	42.67	47.372	35.57
2.1 E 4	277.73	219.68	316.72	240.08	288.69	229.31
2.1 E 5	583.78	465.42	581	464.72	599.28	465.23

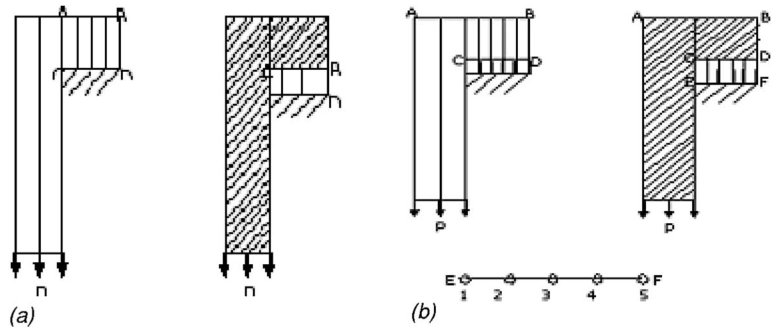

Fig. 2 Bolt models as link and continuum

Table 5 Reactions at nodes on EF: For a continuum and link model

	1		2		3		4		5	
Stiffness	Continuum	Link	Continuum	Link	Continuum	Link	Continuum	Link	Continuum	Link
1	60	60	120	120	120	120	120	120	60	60
10	62	60	120	120	119	120	119	120	59	60
50	69	60	121	120	117	120	115	120	69	60
100	77	60	122	120	114	120	112	120	54	60
1000	134	60	113	120	96	120	95	120	46	60

creased by changing the area as 1, 10, 50, 100, and 1000 mm^2, i.e., increasing the stiffness by one thousand times in steps. Analysis is carried out and reactions at ground nodes (Table 5) are noted.

4 Analysis for Load Transfer Through the Bolted Connection

When the bolted assembly is subjected to an external load, then the amount of this external load shared by the bolt and the plates is different. It is generally said that a well-lighted bolt would share only a small portion of the total load. The bolt is modeled as a continuum and analyzed as an axisymmetric model to evaluate the ratio of the load shared between the bracket and the bolt. The model consists of a bracket and a bolt; bracket, carrying certain loads being secured to a fixed wall by means of a bolt (Fig. 3). An assembly approach is used to construct the model using a uniform coordinate system for the case of an assembly. The bolt pretension is simulated through the temperature change. Compression only link elements are used to simulate the connection between the bracket and the bolt head and between the interface and between the bracket and fixed wall. These link elements are given high stiffness value so that the overall stiffness is not affected. Appropriate constraints are applied to the model. All the nodes are constrained in the Z-direction. Each link element is coupled in the X direction to simulate no relative movement in the radial direction.

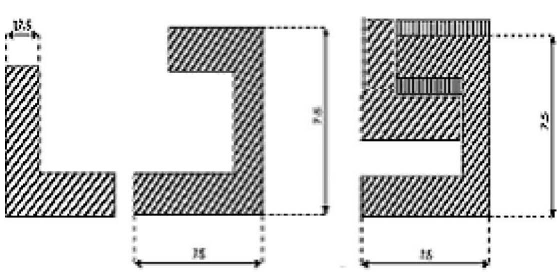

Fig. 3 Bracket and bolt models

As the model is an explicit model, the value of α, i.e., the coefficient of the linear thermal expansion is given zero for the plate and 12 E 6 for the bolt.

Analyses are carried out for various bolt pretensions simulated by temperature $0°C$ (no pretension), $-50°C$ to $-250°C$ in steps of 50 (Table 6). All these analyses are carried out in two steps. The first step is to obtain the remaining tension in the bolt due to compression of the bracket. The next step is to apply a load of 96,200 N on the bracket (which correlates to a shear of 100 N/mm^2 in the bolt). Change in bolt tension due to the applied load is obtained. The result indicates change in the bolt tension as a function of initial tension.

It can be observed that the load shared by the bolt decreases with increasing pretension and becomes almost constant beyond a certain value. The above analyses are carried out for a given rigidity of the bolt and the bracket and subsequently repeated for different relative rigidities. The values of Young's Modulus used are 2.1×10^3 to 2.1×10^7 in steps of 10, keeping the Young's Modulus of the bolt as 2.1×10^5. When the bracket is about two orders less stiff than the bolt, the bolt does not retain any tension as the bracket can deform to a large extent. As such there is no appreciable change in the load shared by the bolt with increasing pretension. But as the bracket becomes stiffer, the picture is altered significantly and for very high stiff bracket 2.1×10^7, the

Table 6 Applied and remaining bolt pretension for a given temperature

Temperature	Applied bolt pretension, kN	Remaining bolt pretension, kN	Bolt tension after load is applied, kN	Increase in bolt tension, kN
0	0	0	100	100
−50	126	67.04	108.62	41.58
−100	252	134.08	156.52	22.44
−150	378	201.13	213.27	12.14
−200	504	268.17	276.96	8.79
−250	630	335.20	344	8.80

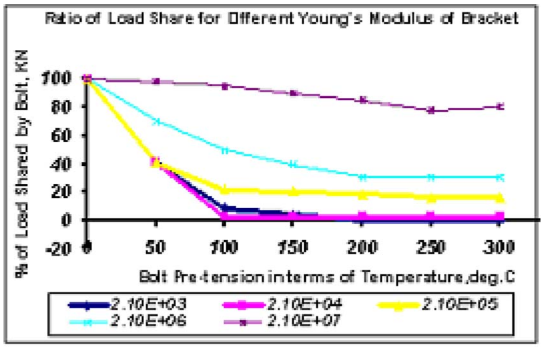

Fig. 4 Load share analysis of bolt and bracket

bolt tension continuously reduces, contrary to stabilizing the trend observed for values 2.1×10^5 and 2.1×10^6 (Fig. 4). For a particular value of ΔT the applied bolt tension is calculated as $\sigma = E.\alpha.\Delta T$.

5 Results and Discussions

Two-dimensional analyses are carried out mainly to determine stiffness of the bolt when represented by the link and as a continuum. It is found that the bolt as a link (for identical conditions otherwise) is about 6% stiffer than the bolt as a continuum. Also, the nature of the compressive pressure exerted by the bolt on the plate (under the bolt head) is significantly different in these two types of bolt models. It is observed that the bolt as a link exerts a uniform pressure irrespective of the stiffness of the plate under the bolt head. But the bolt as a continuum shows a pressure distribution. This is more towards the bolt and decreases away from it. This distribution becomes more and more pronounced as the stiffness of the plate increases. The distribution obtained in the case of a bolt as a continuum appears to be a realistic one and hence it may appear that the bolt as a continuum is a correct way of representing a bolt. Representing the bolt as a link has an advantage in that, it provides modeling ease. But it appears that this may not be the correct way. It is said that in a well-tightened joint the bolt shares only a fraction of the externally applied load. This is established by carrying out analyses on a simple case of a bracket bolted to a fixed wall. The bracket is subjected to a load and the fraction of the load shared by the bolt for various initial tensions are determined. It is observed that the fraction of the load is progressively reduced with more initial tension. The fall is rapid in the beginning and gradually stabilizes to value of about 8% to 9% [9–11].

6 Conclusions

The two important attributes of the bolted joints, the remaining bolt tension and the compressive pressure distribution along the interface, depend upon the type of model used to represent bolt (link or continuum), but not on the type of analysis (2D, 3D, and axisymmetric). The bolt represented, as a continuum is more realistic and the correct way.

The distribution of compressive pressure exerted by the bolt on the plate (under the bolt head) becomes more and more pronounced as the stiffness of the plate increases.

In a well-tightened joint, the fraction of the load shared by the bolt is progressively reduced with an increase in the value of initial tension.

Acknowledgments

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Nomenclature

A = area of cross section of the bolt
E = Young's Modulus
ΔT = change in temperature
P = bolt tension
α = coefficient of linear thermal expansion
σ = total stress

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