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Experimental and Finite Element Analysis of Preloaded Bolted Joints Under Impact Loading

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One of the primary parameters in analyzing bolted joints is preload in the bolt. We have considered several possible preload modeling techniques to analyze the effect of preload on the dynamic response of the bolted joints. Five different methods of applying preload in the nonlinear finite element analysis are evaluated. These methods are "force on bolt and nut", "force on bolt shank", "interference fit", "thermal gradient" and "initial stress method". Explicit and implicit analyses are used for transient response and preload generation in bolt respectively. Time history and shock response spectrum are used to compare experimental and simulation results. Simulation results compared fairly well with the experimental results.

Nomenclature

E = young's Modulus
ε = strain
α = thermal expansion co-efficient
σ = thermal stress
Δt = temperature gradient

I. Introduction

Bolted joints are widely used in automobiles, machinery, airplanes, steel structures, etc. In non-linear dynamic finite element analysis of bolted joints, the modeling of preload is an important factor. While there have been many studies on static analysis of preload on bolts, there is little or no literature available describing the dynamic analysis of the preloaded joint under the effects of shock or impact. LS-DYNA solver is used for the simulation of dynamic behavior of bolted joints. Different preload modeling techniques are available in LS-DYNA (Ref.1). Some of the preload modeling techniques were developed by the National Crash Analysis Center (Ref.2) and Texas Transportation Institute (Ref.3). These techniques use redundant beam and spring elements to get preload. Reid and Hiser (Ref.4) developed stress based clamping model with deformable elements using preload modeling techniques. This technique uses the Initial Stress Solid card in the LS-DYNA solver. The explicit solver is used in transient (dynamic) analysis and implicit solver is used for preload application in the bolted joints. LS-DYNA explicit solver uses dynamic relaxation technique to damp the initial kinetic energy caused by the deformation of bolt shank. In this project we have considered five major preload modeling techniques in the bolted joints: (a) applying equal and opposite forces on the bolt and nut, (b) applying equal and opposite forces on the split bolt shank, (c) interference fit between the nut and plate, (d) applying thermal gradient on the bolt shank, (e) using Initial Stress Solid card in LS-DYNA.

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II.   Problem Description

A. Geometry and Dimensions

The structure used for studying the shock propagation through bolted joints consists of five major parts: Hat section, spacers (washers), flat plate, bolts and nuts. Hex bolts and nuts are used to connect the hat section and flat plate as shown in Fig. 1. The hat section and plate are made from quarter inch (6.35 mm) steel plate. There are four holes (ϕ10.00 mm) drilled on the plate and hat section. The dimensions of the hat section is shown in Fig. 2
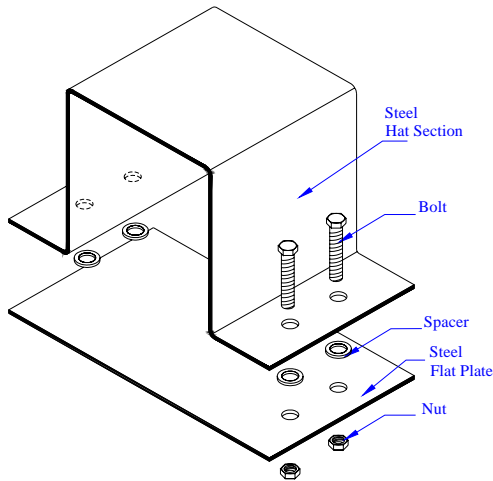
Figure 1. Assembly drawing of the bolted joint structure.
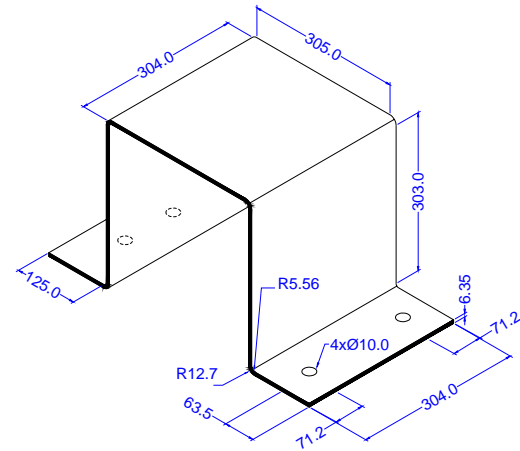
Figure 2. Hat section configuration (dimensions are in mm).

The metric plain washer has been used as the spacer between hat section and flat plate. The narrow plain washer is made for 10 mm screw size. The inside and outside diameter of the washer are 10.85 and 19.48 mm respectively. Class 8.8, M10×1.25 hex bolts and nuts are used to connect the flat plate to the hat section. The bolts and nuts dimensions follow the ANSI B18.2.3.5M-1979, R1989 standard.

B. Material Properties

Bolts, nuts and washers are made from class 8.8 steel. Hat section and flat plate are made from hot rolled ASTM-A36 steel. Table. 1 shows the material properties of each part of the structure (Ref.5).

Table 1. Material properties

Part	Material	Density (Kg/m^3)	Modulus of elasticity (GPa)	Yield stress (MPa)	Poisson ratio
Hat section	ASTM-A36 steel (hot roll)	7850	200	250	0.26
Flat plate					
Spacers (washers)	Class 8.8 steel	7850	207	660	0.3
Bolts					
Nuts					

III.   Experimental Setup and Procedure

The test setup includes the bolted joint configuration, accelerometers, impulse hammer, and a laptop computer. Figure. 3 shows the bolted joint configuration hanging from a large steel support frame by 1-m long steel wires. Two accelerometers are mounted on the hat section and plate (one on the hat section and one on the plate). The accelerometers and impact hammer are connected to the data acquisition board and hardware.

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Pulse LAB is the data acquisition software, which uses SI units. The units for the accelerometer and hammer are (m/s^2) and (N). The Pulse Lab software and DAQ hardware is made by Brüel & Kjær. The impulse hammer and accelerometers are made by PCB Piezoelectric Inc. The sensitivity of the hammer is 0.225 mV/N, with the measurement range of ± 22,000 (N) peak. The mass of the hammer is 1.1 (kg). The accelerometers have a sensitivity of 10 mV/g, with the measurement range ± 500g peak. The frequency range is 1.0 to 10,000 Hz. The weight of each accelerometer is 0.5 grams. The load cell in the hammer measures the impact force applied to the system. Figure. 4 shows a force curve captured by the hammer. The same force curve is used as the loading for the finite element model. The impulse time of force is 1.6 ms.

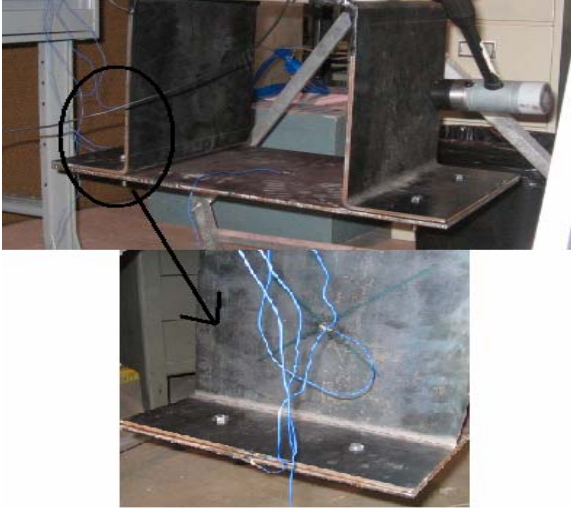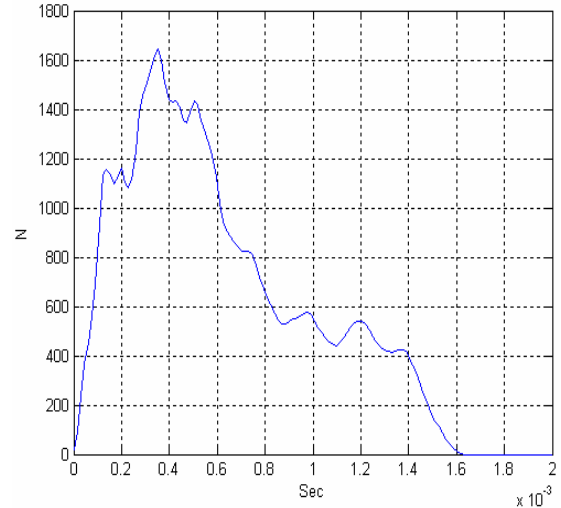**Figure 3. Experimental setup.**

Figure 4. Force curve captured by the impulse hammer.

A. Deterministic/Repeatability of Experiment

The experiments carried out to study the shock propagation through the bolted joints are deterministic or repeatable. "If an experiment producing specific data of interest can be repeated many times with identical results (within limits of experimental error), then the data can generally be considered deterministic. Otherwise the data is random" (Ref.6). The Fig. 5 shows the force and acceleration curves for three trials carried out on the structure. The peak force of 2000 N is applied on the structure and the corresponding response is measured. The response is the same for all the three trials. This implies that the response of the structure is deterministic and not random.
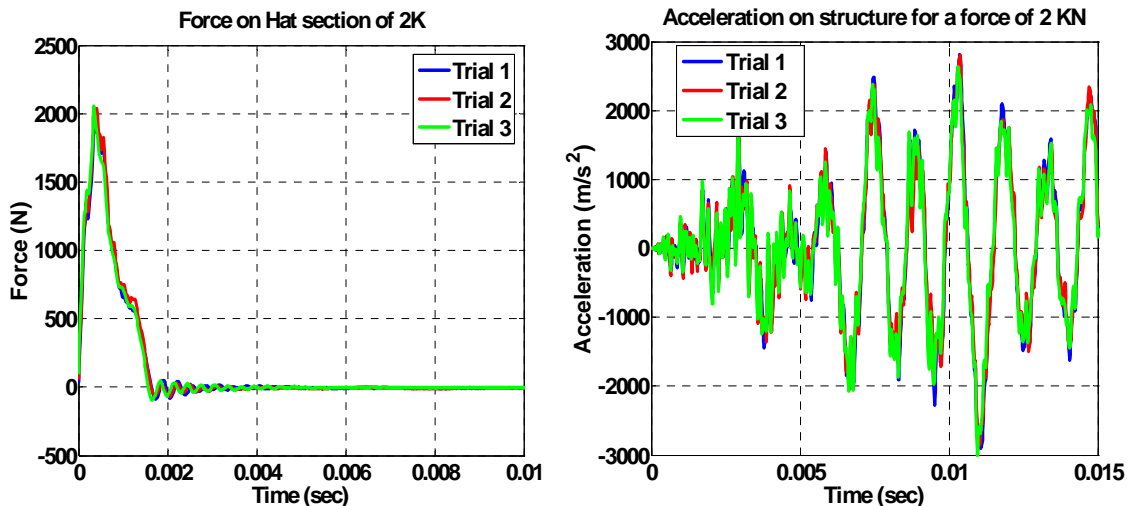

Figure 5. Force curve and Time History response of the structure.

IV.   Finite Element Analysis

Five preload modeling techniques for bolted joints are discussed in detail. Contacts are defined between the bolt head and plate, nut and plate and between two plates. No boundary conditions are applied on the structure in the computational model. It is free to move or rotate in any direction.
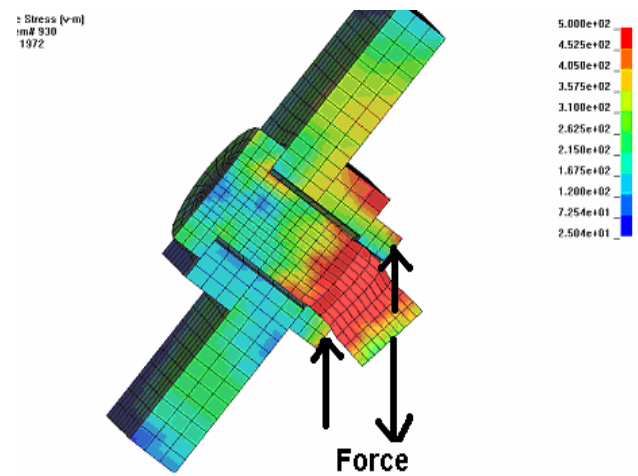
A. Applying Equal and Opposite Forces on the Bolt and Nut

The LS-DYNA card, CONTROL_IMPLICIT_GENERAL, has an option of switching between implicit and explicit analysis during a simulation. The preload force is applied on the bolt and nut during implicit analysis and then it is switched to explicit analysis for shock or impact analysis. The force applied on the bolt and nut is shown in Fig. 6. The force increases linearly for 1 millisecond and then is constant throughout the simulation. The constant force gives the required pre-stress in bolted joint. By varying this force the required pre-stress on the bolt shank can be obtained. Figure. 6 shows the stress vs. time plot on the bolt shank. The stress increases for 1 millisecond and there after it remains constant. The stress is proportional to applied force.
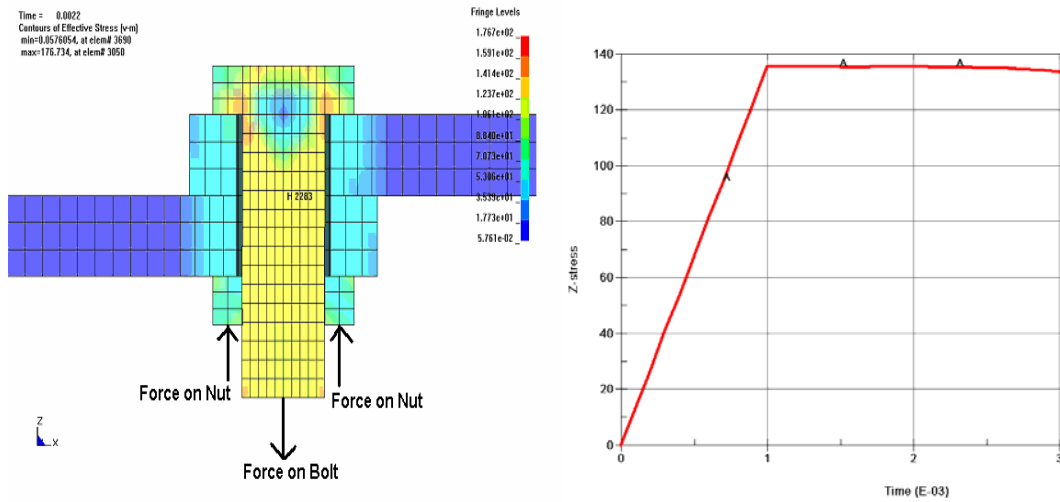
Figure 6. Bolted joint with load on bolt and nut, stress on the bolt shank.

This method of getting pre-stress in the bolted joints has a disadvantage. Figure. 7 shows the two plates connected with bolt and nut assembly. The pre-load is applied on the bolt and nut during implicit analysis. During explicit analysis the complete structure is rotated in transverse direction. The force applied on bolt and nut during implicit analysis are continued in explicit analysis. The force being a vector depends both on magnitude and direction. Initially the bolt is in Z-direction and the forces applied are in Z-direction. When the structure is rotated, the bolt axis changes with respect to time but the force applied remains to stay in the Z-direction. This causes the bending in bolt shaft and the stress in bolt exceeds the yield strength. This is shown in Fig. 7. Therefore modeling pre-stress on the bolt and nut assembly by applying force during implicit

Figure 7. Bending stress due to rotation of structure.

analysis is suitable only when there is no rotation of bolt. This may be resolved by defining the force direction not along any axis, but defining based on vector created by three nodes.

B. Applying Equal and Opposite Forces on the Split Bolt Shank

This method is similar to the previous method and the only difference is that instead of applying force on the bolt end and nut, here the bolt shank is split at the center and the force is applied on the split face as shown in Fig. 8. The force applied on the two faces of the shank is equal and opposite. Tied contact is used between the nut and the bolt shaft or the nodes on the nut and bolt can be merged.
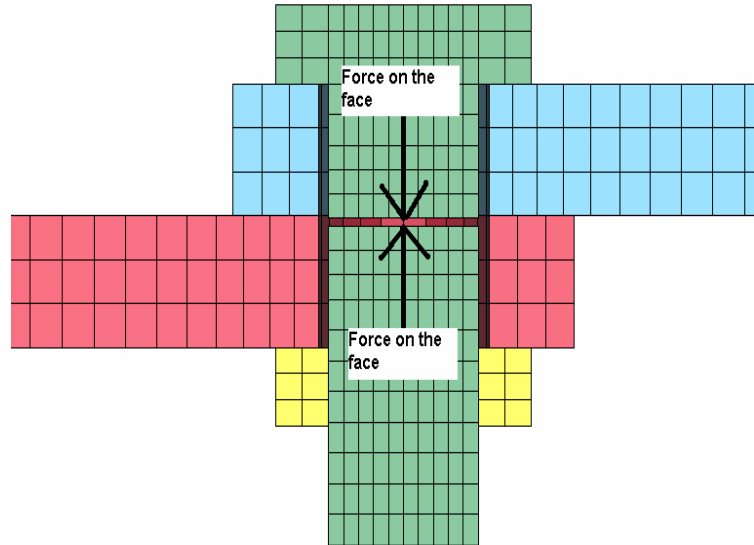
C. Interference Fit Between the Nut and Plate

This is another way of getting the pre-stress in the bolted joint. Here the nut is modeled in such a way that it initially penetrates into the plate as shown in Fig. 9. The contact is defined between the nut and plate. When LS-DYNA starts solving this problem it recognizes the contact and pushes the nut. The nut and bolt are having the tied contact. When the nut moves away

Figure 8. Bolted joint with preload.

from the plate, it elongates the bolt shank, which induces the tensile stress as shown in Fig. 9. This is the required pre-stress on the bolt and nut assembly. This is a trial and error method because to get the required pre-stress we need to find the initial penetration of nut into plate. By doing two trials we can plot the stress induced in bolt vs. initial penetration curve. By interpolating or extrapolating we get the required initial penetration of nut into plate.
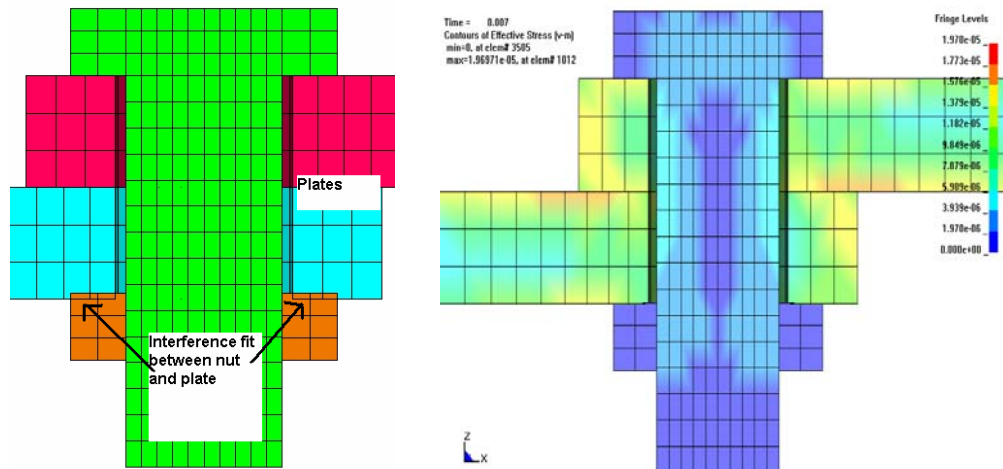
Figure 9. Bolted joint with interference fit.

D. Applying Thermal Gradient on the Bolt Shank

This is the widely used technique for getting pre-stress. This technique is available in all the commercial FE software programs. The thermal gradient is applied on the bolt shank as shown in Fig. 10. Here the temperature of the bolt shank is reduced, that is the bolt shank shrinks causing the tensile stress in the bolt.

Thermal strain is calculated by the following equation.

$$\varepsilon = \alpha.\Delta t$$

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Thermal stress is calculated as

$$\sigma = E.\varepsilon = E.\alpha.\Delta t$$

In the above equation 'E' and '∝' are constant. Therefore the thermal stress is proportional to the temperature gradient. Therefore by varying the temperature, the desired pre-stress in the bolt can be achieved.

The LS-DYNA material card MAT_ELASTIC_PLASTIC_THERMAL is used for defining the temperature dependent material property for bolt shank. Along with this card, LOAD_THERMAL LOAD_CURVE is used for defining the temperature vs. time curve. Dynamic relaxation is carried out before the explicit analysis in LS-DYNA. The Fig. 11 shows the Von Mises stress on the bolt shank. At time t = 0, the stress on the bolt shank reaches the required (maximum) value and the remains constant through out the simulation.
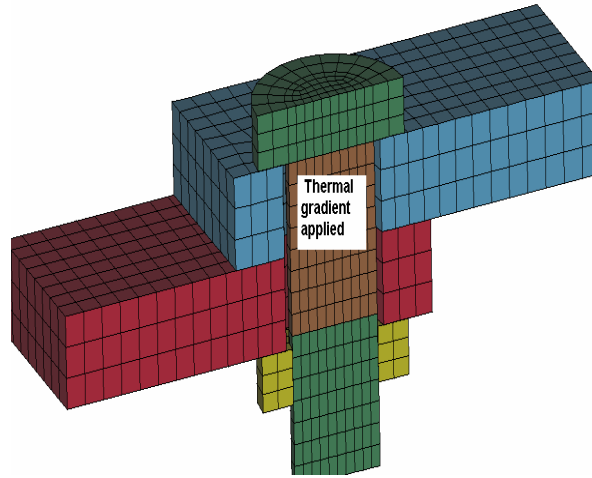

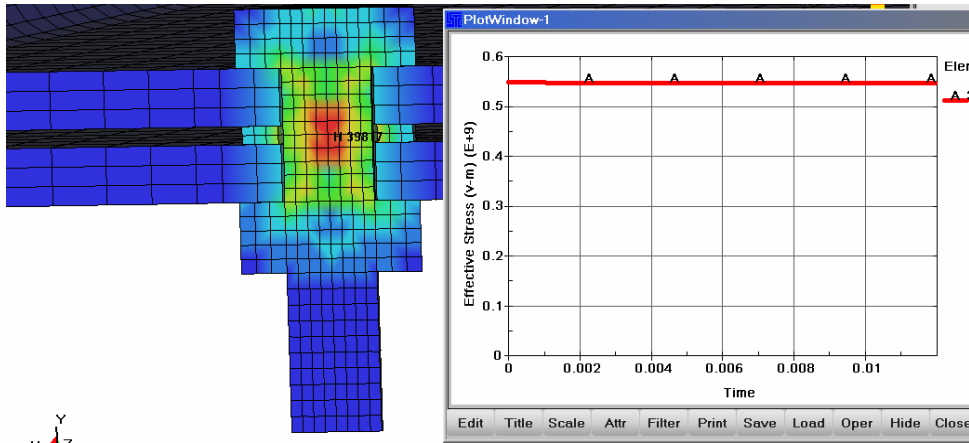**Figure 10. Bolted joint with thermal gradient.**

Figure 11. Pre-stress induced in bolted joint due to thermal gradient.

E. Using INITIAL_STRESS_SOLID Card in LS-DYNA

This method of getting pre-stress in bolted joints is available only in LS-DYNA solver. The LS-DYNA card, INITIAL_ STRESS_SOLID, is used for defining the pre-stress in the bolted joints. Using this card the initial stress and strain (Normal stress, Shear stress and plastic strain) can be defined on solid elements. These normal stresses are in X, Y, Z-directions.

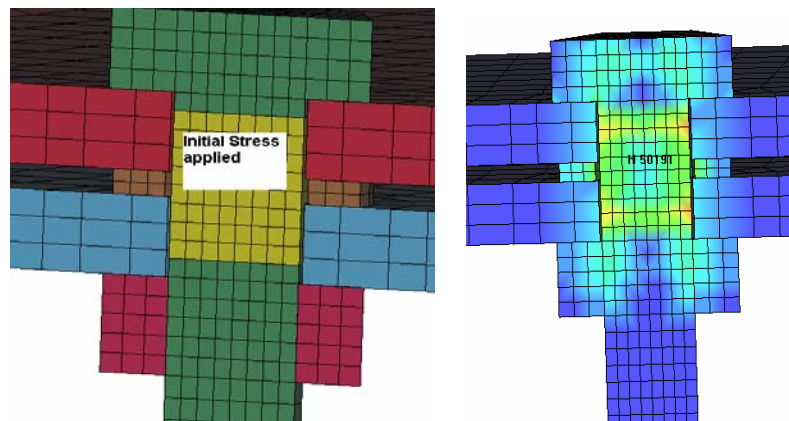Figure. 12 show the bolted joint used for connecting two plates. Initial stress is applied on

Figure 12. Bolted joint with initial stress.

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the bolt shank. The bolt shank will have a tensile stress when the nut is tightened on the bolt. Therefore the tensile stress (Positive stress) has to be defined for the bolt shank. The axis of bolt is in Y-direction. Therefore y-stress is defined to all the elements in the bolt shank. Dynamic relaxation is applied for this method to damp the kinetic energy produced during the deformation of plates and bolt. Figure. 12 shows the Von Mises stress during the explicit analysis of this structure. The stress vs. time plot for an element on the bolt shank is shown in the Fig. 13. The stress is almost constant through out the simulation.
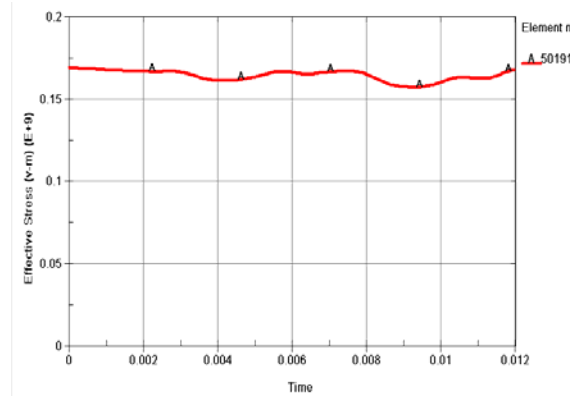

Figure 13. Stress vs. time plot on the bolt shank.

V.   Results

The structure used for studying the shock response through the bolted joints is shown in Fig. 14. Acceleration is measured at two points on the structure – one on the hat section and one on the flat plate as shown in Fig. 14. Washers are used between the hat section and flat plate. LS-DYNA solver is used to simulate this experiment. Explicit solver is used to get the time response. The input force for the simulation is the force curve from the impact hammer as shown in Fig. 4. The run time is 10 milliseconds.
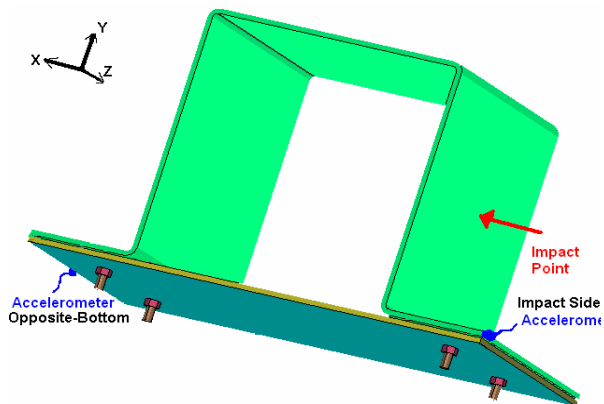

Figure 14. Hat section with plate used in dynamic response of the bolted joints.

Figure 15. Structure showing the constant pre-stress of 470 MPa.

Thermal gradient and initial stress methods are used to preload the bolt in the simulation. Three preload conditions are studied in this project. The preload of 10.5KN, 37.5 KN and 50 KN corresponding to torque of 21 Nm, 75 Nm and 100 Nm are used. The effect of preload on the structure is studied. Figure. 15 shows the pre-stress of 456 MPa in the bolted joint for the preload of 37.5 KN. The pre-stress is constant throughout the transient analysis.

The FFT analysis of the structure for different preload is shown in Fig. 16. The three FFT curves corresponding to bolt torque of 100, 75, 21 NM are identical. This shows that the preload of the bolt have no effect on the response of the structure. The Table.
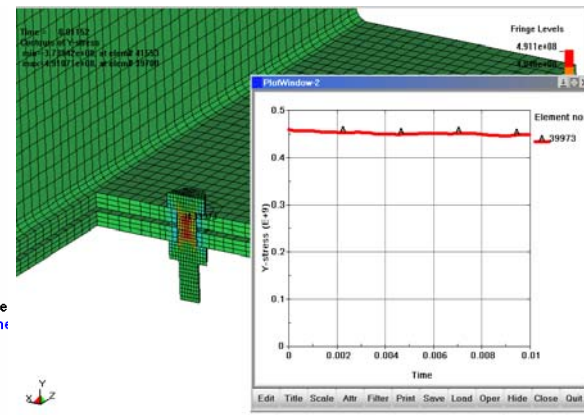

Figure 16. FFT of hat section for 100, 75 and 21Nm Torque.

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2 show the mode number and natural frequency of the structure.

Table- 2 Natural frequency of structure

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Natural Frequency (Hz) (For 100, 75, 21 Nm preload)	68	124	196	244	368	416	456	644	684	732	808	872	904	1100

Figure. 17 shows the acceleration vs. time plots for the structure measured at two points – one on the hat section and one on the plate. These results correspond to preload of 50 KN (Torque-75 Nm). The blue and red curves represent experiment and simulation results respectively. The shock response spectrum is plotted for these two points in Fig. 18.
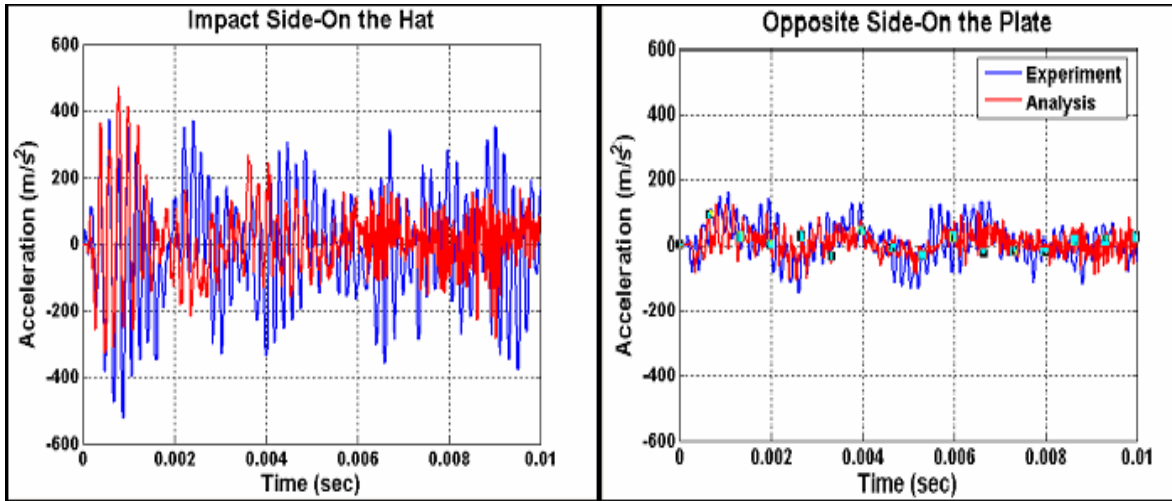
Figure 17. Time History response on the structure.
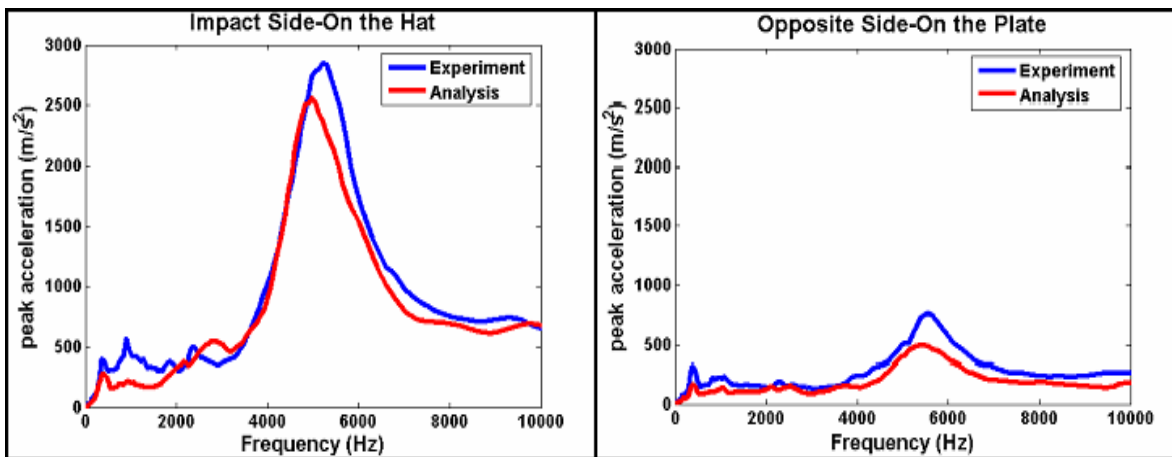
Figure 18. Shock response spectrum.

VI.   Conclusion

All five methods can be used in getting preload in bolted joints. But the thermal and initial stress methods are suitable for non-linear dynamic problems. These methods are simple and easy to model and can be used for static and dynamic analysis. Natural frequency of the structure is same for 100, 75 and 21 Nm torque on bolt. This concludes that the response of the structure will be same for any kind of preload. As it can be seen in Fig. 15 and

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Fig. 16, there is a fairly good match between the experiment and analysis on the hat section acceleration. However, the analysis gives lower amplitude acceleration than the experiment. There is more than 50% reduction in the amplitude of the acceleration after the joint. There are some more parameters, which need to be studied to understand the shock propagation through bolted joints such as clearance between the bolt shank and the structure, washer thickness and material, and size of the structure.

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