Finite Element Modeling of Preloaded Bolt Under Static Three-Point Bending Load

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Abstract

The objective of this project was to develop innovative lightweight mine-protected fasteners for blast protection appliqués. Blast protection appliqués are used on tactical and combat ground vehicles as a method of deflecting or mitigating the effects of anti-vehicular mine blasts or attack by Improvised Explosive Devices (IEDs). A critical and weakest component of these appliqués is the fastener joints. Currently, industrial bolts are commonly used for attaching blast protection appliqués to vehicles due to simplicity. However, under blast conditions, these bolts can often shear off causing secondary fragments and projectiles which may impact the vehicle and crew, causing additional damage and injury to the vehicle personnel.

This study focused on conducting three-point bending tests to evaluate different bolt materials. Bolt preload or stress initialization was simulated via LS-DYNA® Implicit with two separate analyses. Also a similar two-step initial strain analysis was performed using NEiNastran. The simulated results will be compared with test data. Future work will include finite element modeling and testing of fasteners under dynamic, ballistic, and blast loads.

Introduction

Fastener joints or connections are the simplest method of installing blast protection or armor panels onto a military vehicle, but are often the weak parts of the armor kit. The joint design is no doubt a great challenge for attaching additional vehicle kits to the vehicle. The performance of these joints under blast threat or ballistic impact is not well understood because the blast and ballistic loadings are dynamic events.

Common joint connection methods include bonding, welding, and mechanical fastening. For mechanical fastening, bolted connections are designed to hold two or more parts together and generally consist of head, stud, nut, and washer. Because of different loading conditions, especially under the dynamic blast event, bolted connections can separate due to bolt failure. To minimize this effect, a pretension is applied to the bolt to ensure that the connection will not separate, provided the applied load remains less than the pretension. Bolts can take axial or shear loads, or combination of axial and shear loads. Shear loads transmitted to the bolt are due to joint members sliding or by frictional force.

1. NeiNastran Initial Strain Analysis

To simulate the bolt preload, tension load is applied to the two cut bolt faces in opposite directions. The bolt is pretensioned and analyzed to create the initial strain. Only strain state at the end of the analysis can be written to a .BDF file. The strain data saved in the .BDF file is then put back into the entire model as an initial strain loading condition for secondary analysis.

2. LS-DYNA® Stress Initialization

The bolt preload is applied similar to the first analysis in NeiNastran. An ASCII file called DYNAIN is created at the end of the analysis. The DYNAIN file contains the new nodal coordinates, and the stress and strain tensors for the elements. The data contained in the DYNAIN file can then be used as the basis for second analysis with the residual deformations, stresses and strain from the first analysis.

3. Finite Element Model of a Three-Point Bending Sample

A finite element model of a three-point bending sample was prepared for this study. The geometry and material properties of the components in the finite element model are listed below and in Table 1. All the components were modeled by using LS-DYNA's MAT03 (*MAT_PLASTIC_KINEMATIC) or by using NeiNastran's bi-linear elasto-plastic material model.

Geometry:

Beam : 2 x 16 x ¼ with 12 inches span
Spacer Block: 2 x 2 x ½ in.
Bolt : 3/8 in. diameter

Property	Steel SAE 1020	Grade 8	Steel RHA
Component	Beam	Bolt/Nut	Spacer Block
Density ($lb.s^2/in^4$)	7.3E-4	7.3E-4	7.3E-4
Elastic Modulus (psi)	29.7E6	3.0E7	28.6E6
Poisson's Ratio	0.3	0.3	0.3
Yield Stress (psi)	5.08E4	1.3E5	1.914E5
Tangent Modulus (psi)	9.22E4	1.73E5	2.625E5
Failure Strain	N/A	0.12	0.12

Table 1 – Material Properties

4. Bolt Preloading

4.1 NeiNastran

A preload of 4,200 lbs was applied to the two cut mid-sections of the bolt in opposite directions as depicted in Figure 1. Rough contact type (PTYPE=4) was defined between beam and spacer block to ensure no sliding between the contact surfaces, yet allow contact areas to open or separate. Areas with large gaps in CAD geometry required cleanup to be recognized as contact areas. The nodes on the two cut surfaces were merged during second analysis under static loading.

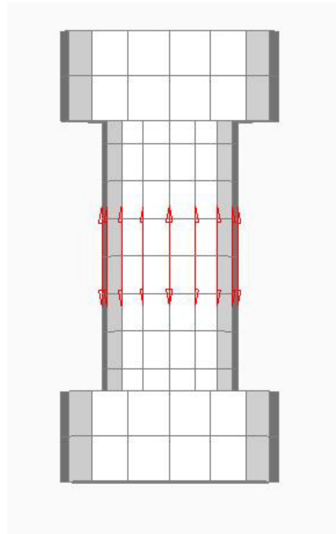
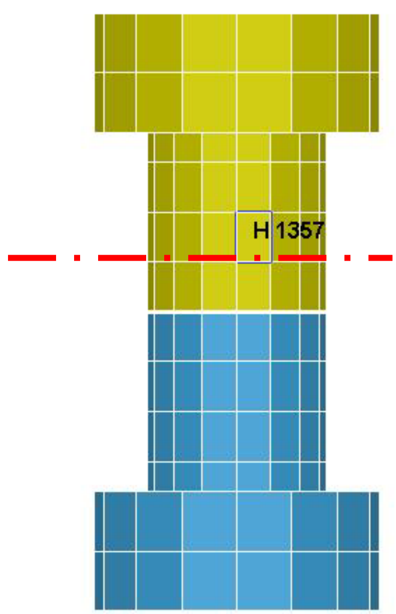


Figure 1 – Bolt with Middle Section Cut

4.2 LS-DYNA

Using the same mesh and similar to NeiNastran, the preload was applied to the two cut mid-section but with an initial 0.008 in. gap. Since NEiNastran only writes out the strain data, there is no need to create a gap or clearance between the two cut surfaces. The gap will close when the preload is applied. The two cut faces become tied by using LS-DYNA's *CONTACT_TIED_SURFACE_TO_SURFACE. Higher preload requires a larger gap. Contact between components was handled with a *CONTACT_AUTOMATIC_SINGLE_SURFACE. The Z-stress of element 1357 has been monitored as shown in Figure 2. It can be seen that the maximum Z-stress is equal to the preload divided by the bolt cross section area.



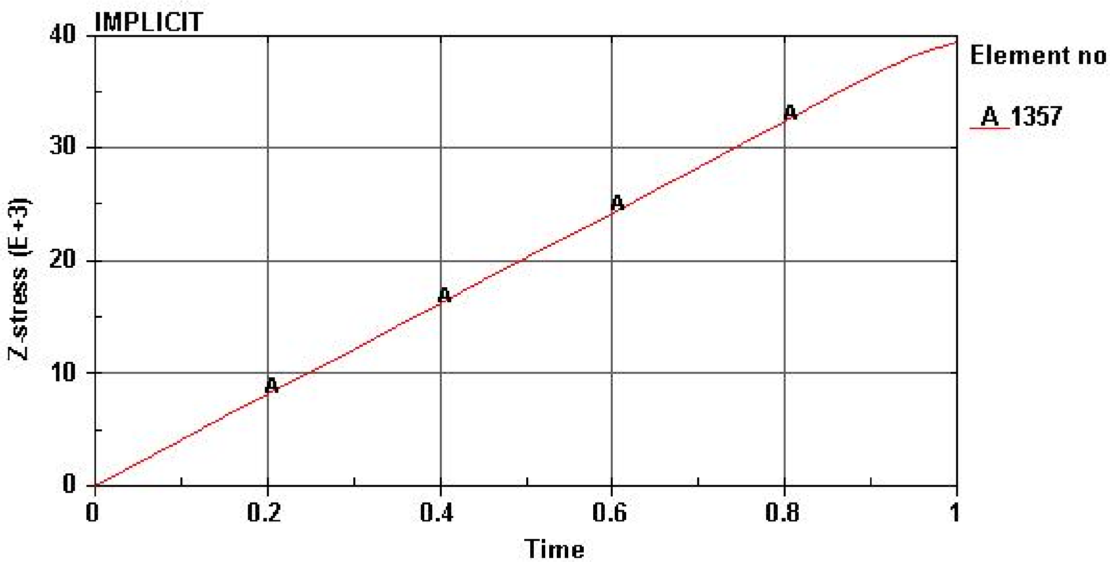
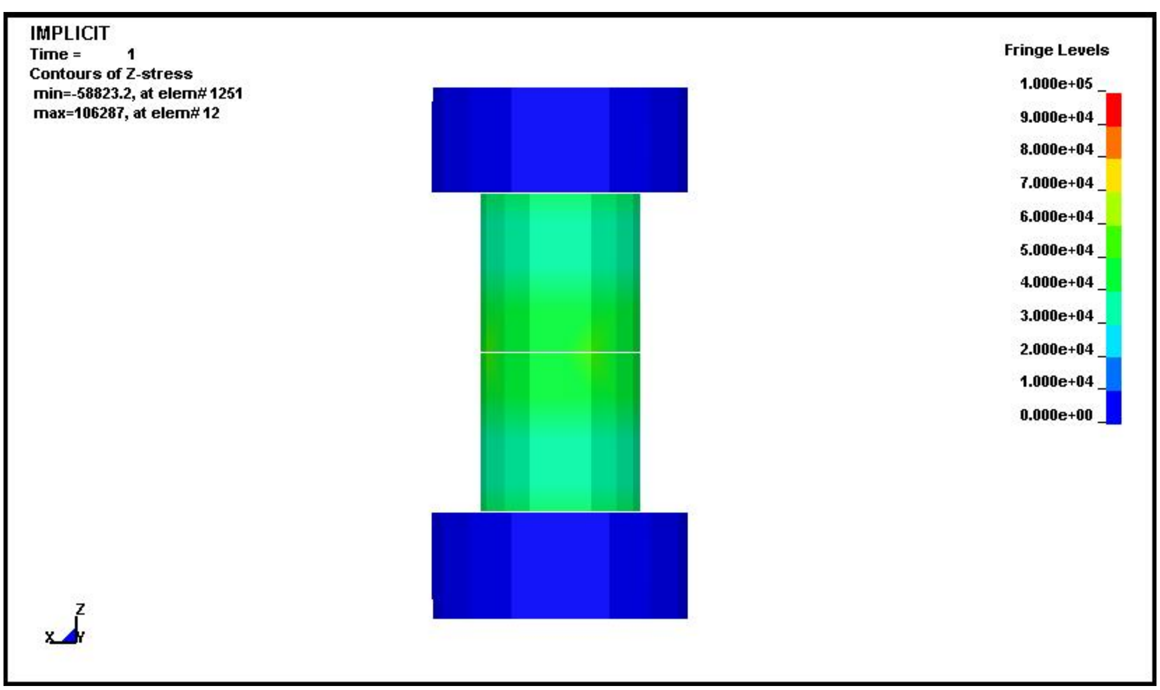


Figure 2 – Bolt Preloading

5. Results from Static Loading

Figure 3 represents the bolt preloading Z-stress from both codes. It can be noted that the results are in good agreement each other. Figures 4 shows the beam deformation and Figure 5 views the bolt effective stress when the beam subjected to 4,000 lbs static load in the mid-span of the beam. The NeiNastran tends to under-predict the maximum beam deformation by 18% compared to LS-DYNA. The reason could be due to the contact treatment in each code. The LS-DYNA analysis clearly shows that the beam end and spacer block separates and the top bolt head rotates more than NeiNastran.



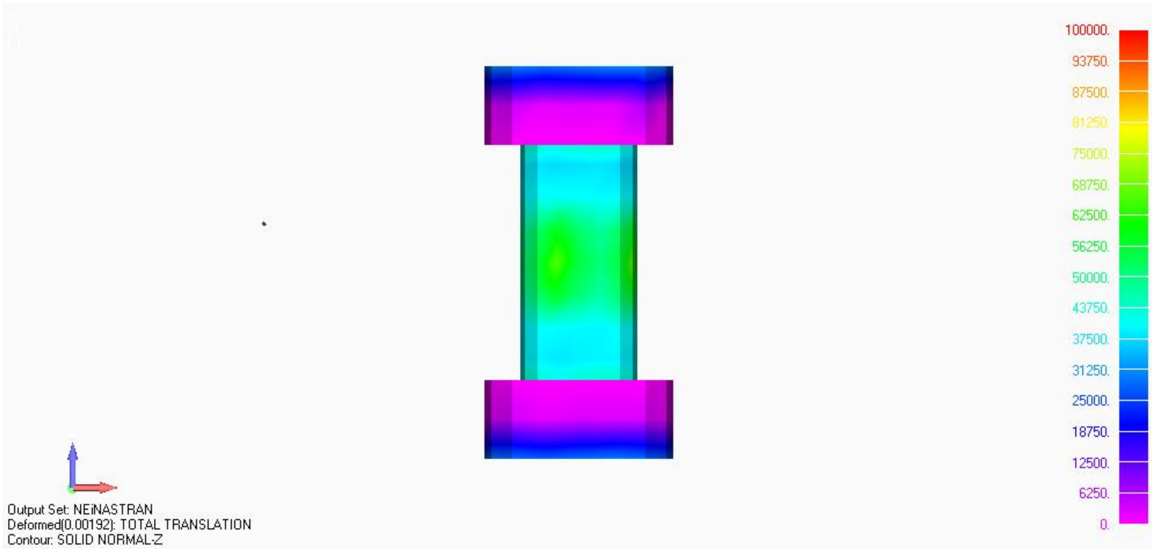
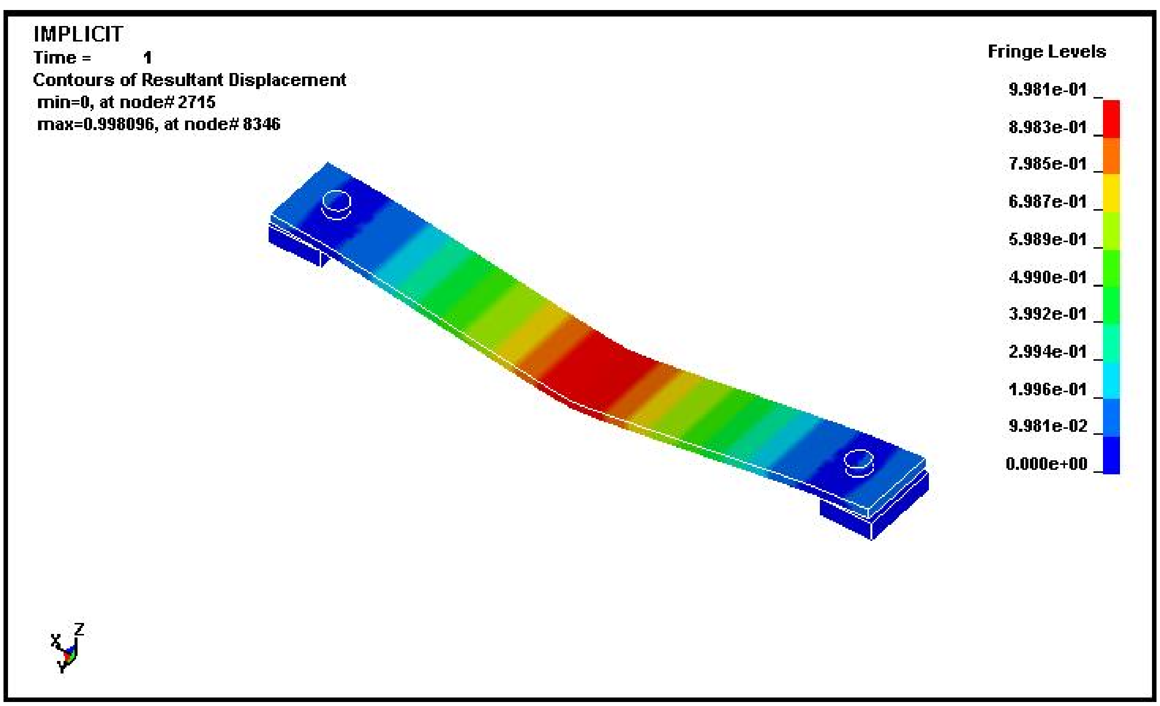


Figure 3 – Bolt Preloading Z-Stress



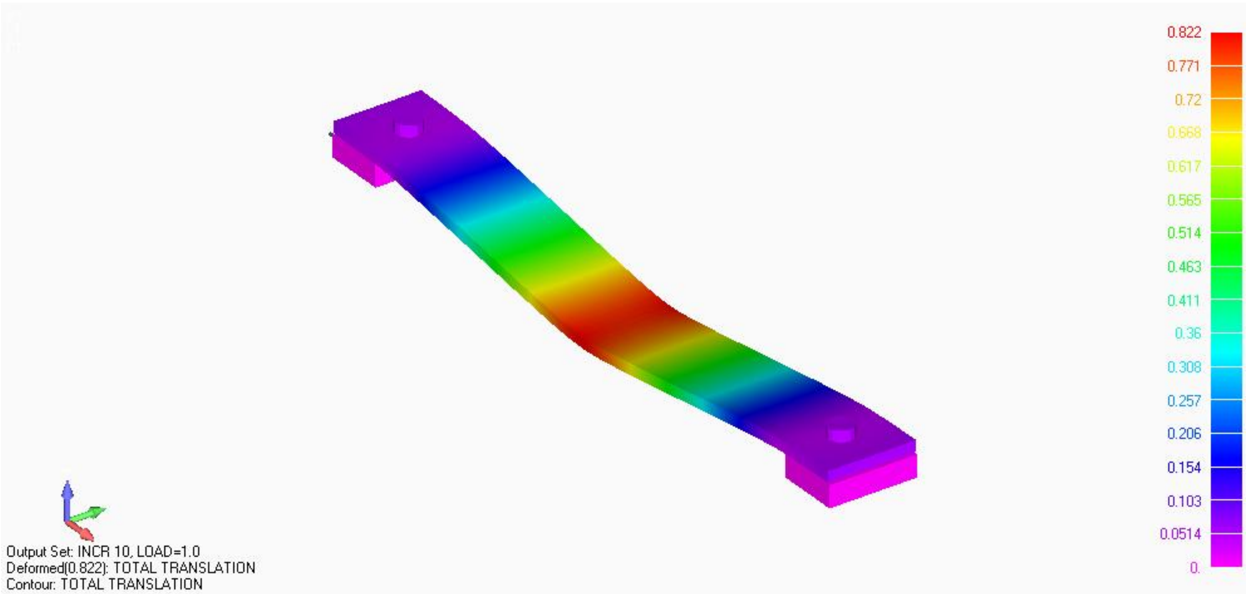
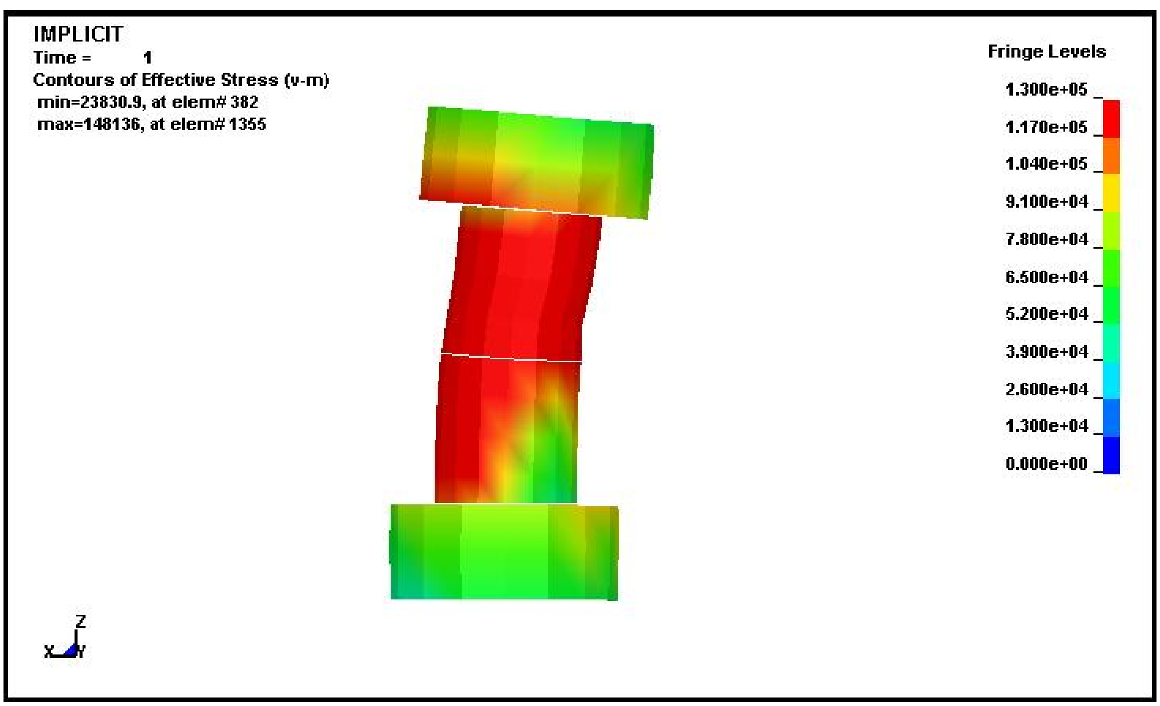


Figure 4 – Beam Deformation



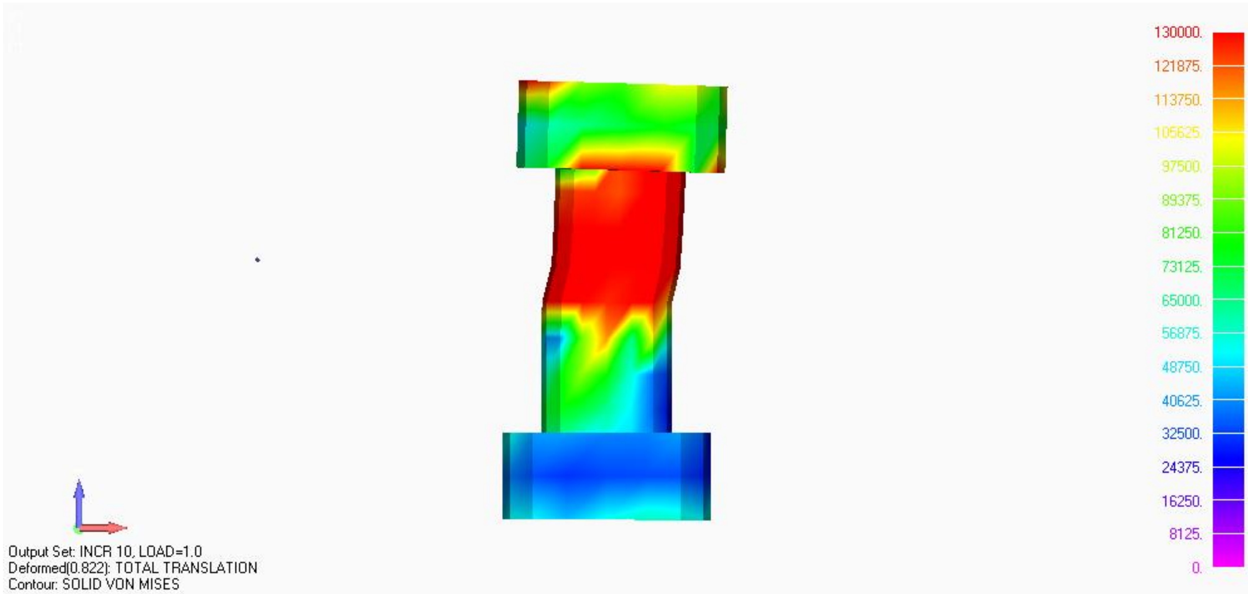


Figure 5 – Bolt Effective Stress

6. Bolt Failure Analysis

LS-DYNA allows failure analysis of the model based upon the plastic strain at failure. Finite element analysis was conducted to compare results with and without bolt preloading. Each analysis was terminated with fatal error message that nonlinear solver failed to find equilibrium and we assumed that the bolts failed to hold the beam at this point. The simulation results are summarized in Figures 6-8. Figure 6 indicates less beam deformation under the same static load when the bolt is preloaded. Also the preloaded bolt fails at higher static load. The effective stress plot at element #1357 (see Figure 2) indicates early stress reduction when the bolt is preloaded as shown in Figure 7. The same observation is shown in Figure 8 for the normal load plot at the bolt cross section cut was shown in Figure 2. In addition, it is interesting to note that, with preload, the peak normal load never exceeded the preload. This may be due to the fact that contact forces do not carry over from the preloading analysis to the second analysis. However, in Reference 6, when *INITIAL_STRESS_SECTION was used to prescribe preloading on a section of bolt solid elements using LS-DYNA's explicit dynamic relaxation method, the bolt preload didn't drop much and almost remained constant at the beginning under blast loading condition (Figures 9-10).

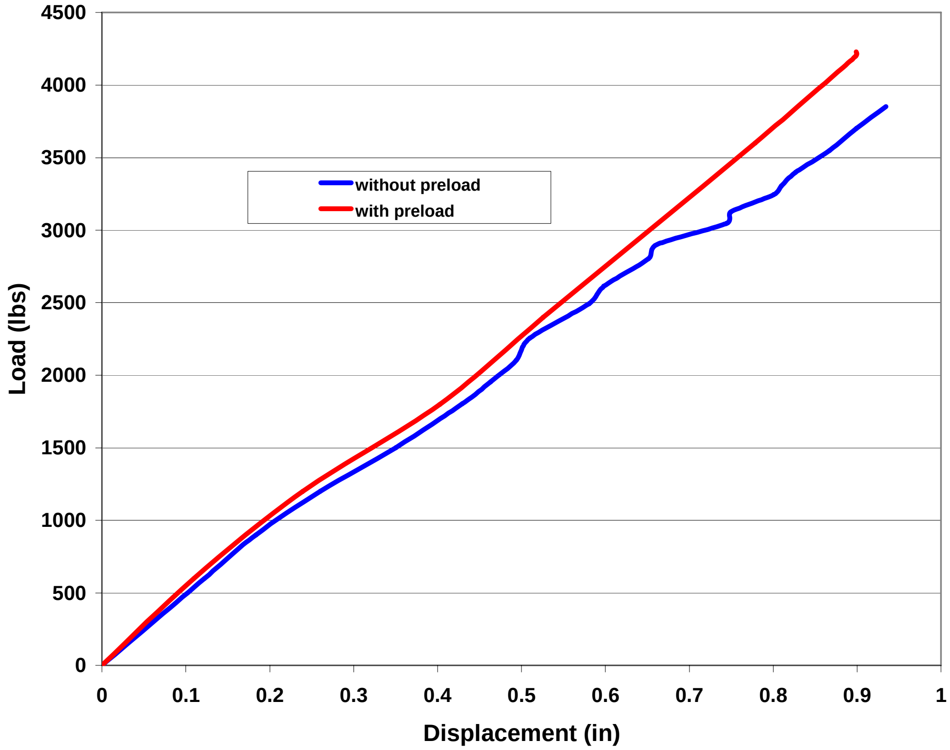


Figure 6 – Load vs. Displacement

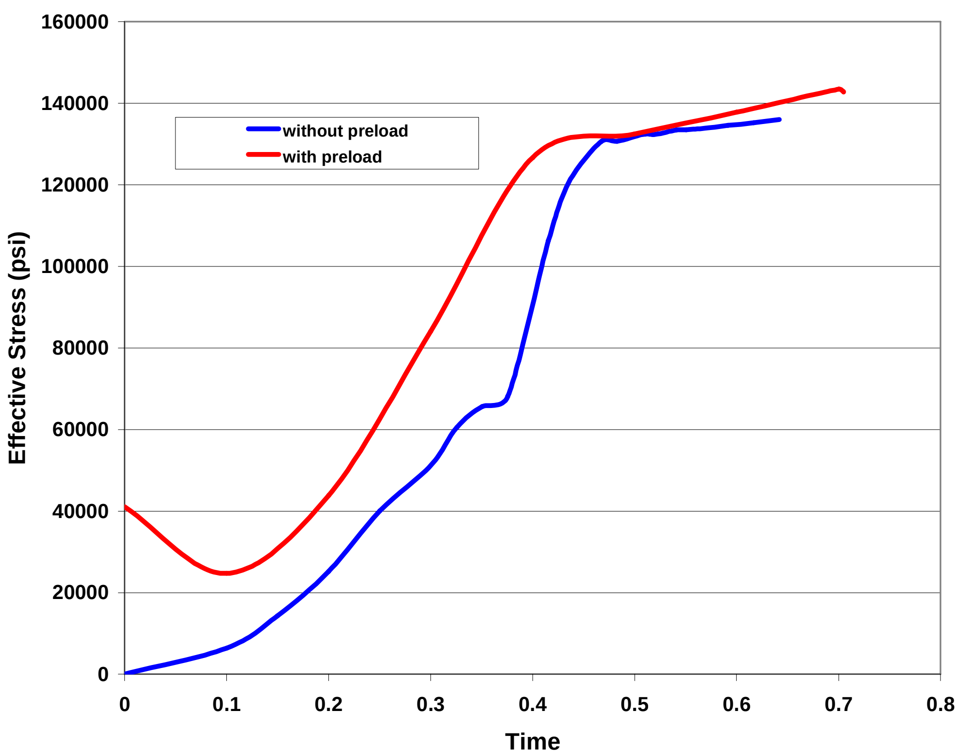


Figure 7 – Bolt Element Effective Stress

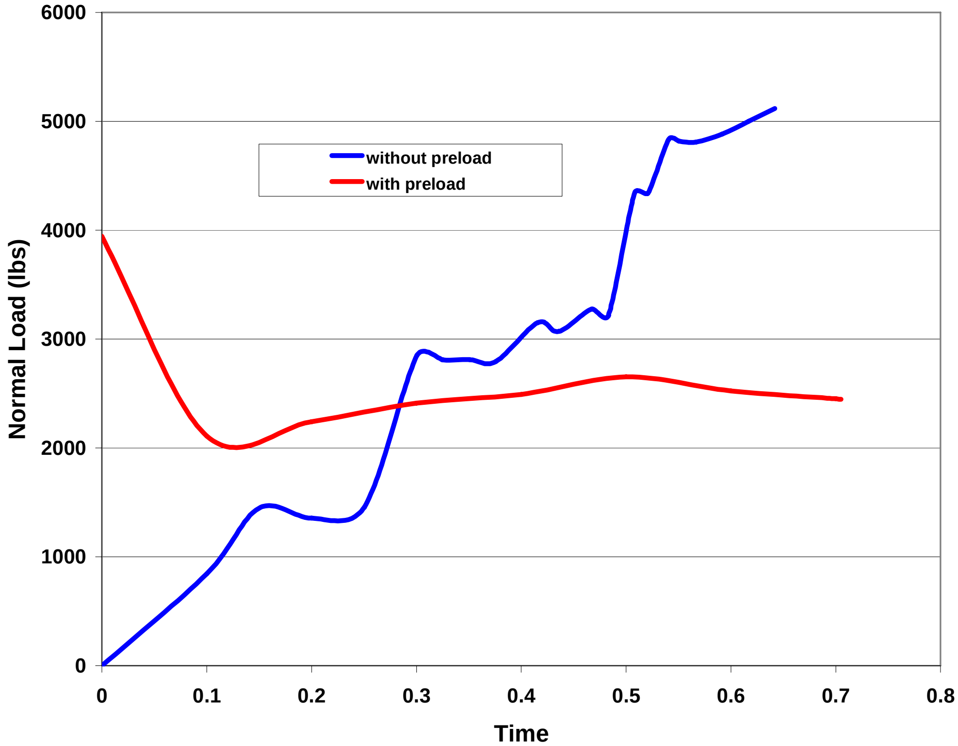


Figure 8 – Bolt Normal Load Due to Static Load

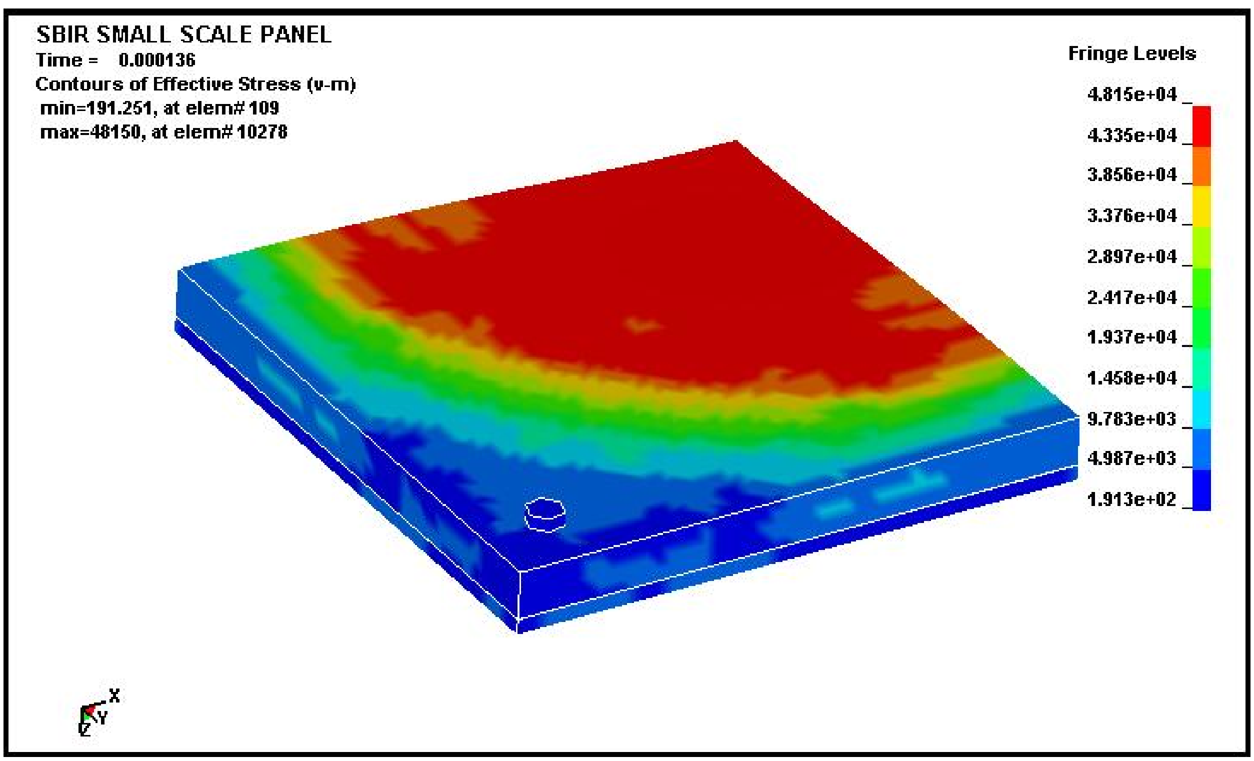


Figure 9 – Blast loading on an Armor Plate

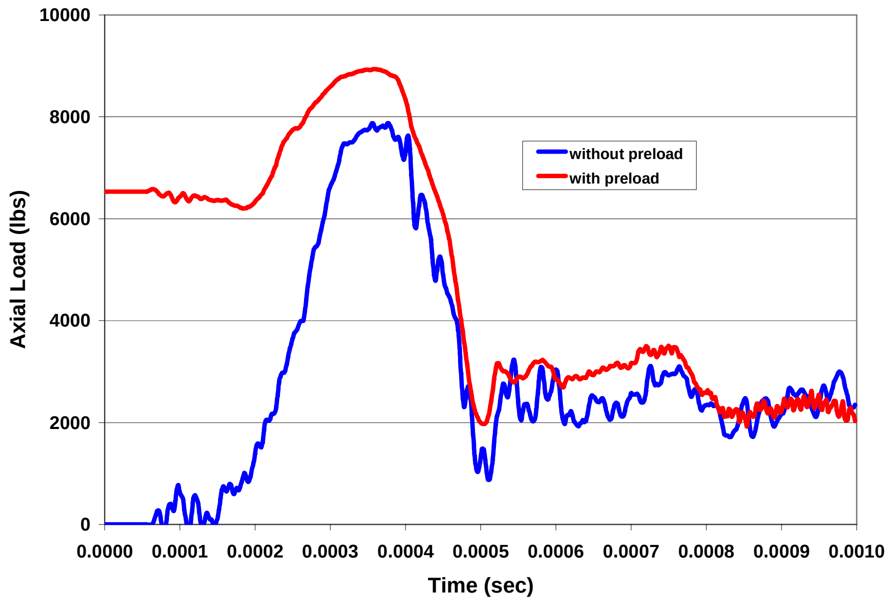


Figure 10 – Bolt Normal Load Due to Blast Load

7. Conclusions

- Finite element results showed good agreement between NeiNastran and LS-DYNA simulation codes
- LS-DYNA is more robust when simulating contact between components with large gaps
- Element failure can be simulated using LS-DYNA
- Importance of bolt preloading has been demonstrated
- Including contact forces in DYNAIN file may improve simulation results

References

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