

Bolted Joint Representation in LS-DYNA[®] to Model Bolt Pre-Stress and Bolt Failure Characteristics in Crash Simulations

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Abstract

During the vehicle crash event (especially vehicles involving light and heavy commercial vehicles where bolted connections are predominantly used) bolted joints behavior, in terms of deformation and failure, play significant role in detecting the level of occupant protection offered by the vehicle structure. The current FE modeling techniques, for bolted joint representation in crash FE models, pose various limitations in terms of simulating the real life bolted joint behavior with explicit codes like LS-DYNA. The present bolt modeling techniques do not address the important aspects of bolted joint like

- *pre-load/pre-stress representation in the bolt,*
- *bearing stresses between bolt shank and clamped plates, clamping forces between plates*
- *Friction between bolts and plates and failure modeling of bolting joints.*

This paper describes FE modeling methodology, for bolted joint representation in crash FE models, for crash simulations using LS-DYNA. Two alternative options are proposed for modeling of bolted joint, either with beam element or with solid hexa elements so as to address the above mentioned aspects of bolted joint in crash simulations. The proposed FE modeling methodology is validated with theoretical calculations and experimental test results. The proposed bolt modeling methodology will help to achieve accurate prediction of structural behavior in crash load cases where bolted joints are predominantly used in crash load paths, such as cabin structure assessment with pendulum impacts, assessment of under run protections devices etc.

Introduction

Bolted connections are invariably used on the vehicle structures for the assembly of various structural components. In the event of vehicle crash, these bolted joints are heavily stressed and some times fail due to the severe impact loading thus affecting the structural integrity of the vehicle structure. This type of failure of bolted joints affects the overall safety protection (crashworthiness) offered by the vehicle and may also result into non compliance of legal passive safety requirements. Hence during the digital product development period it becomes very important that bolted joint strength is accurately assessed under crash loading conditions and optimal strength is ensured for bolted joints which lie in the load paths. During crash simulations using explicit software like LS-DYNA it becomes very important that bolted joints are appropriately modeled in FE context and its realistic impact behavior is accurately simulated during full vehicle crash simulations.

Figure 1 shows typical forces equilibrium in bolted connections where bolted joint is subjected to shear loads. When plates are clamped with help of bolt tightening, pre-load which is tensile in nature is generated in the bolt shank. Whereas clamping force which is compressive in nature, acts on the clamped plates balances the tensile load in the bolt shank. When shear load is applied to the bolted joint, bearing stresses are induced due to interaction between the shank and the plates. Frictional forces present between plates, opposes the relative motion in bolted joint if sliding of the plates are allowed.

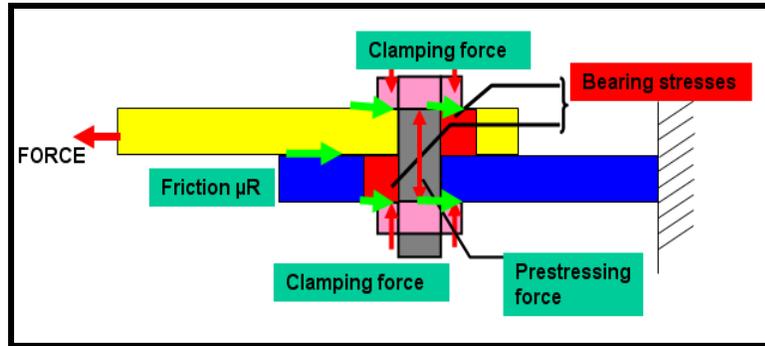


Figure 1- Bolt joint with forces and stresses

Conventionally bolted joints are modeled with beam with spider (rigid link) without any pre-load for crash simulations. This modeling technique has limitations with respect to its ability to represent bolt preload, plate clamping forces and bolt failures in FE models. In the following sessions two alternative options are proposed for FE modeling of bolted joint (with beam element and with solid hexa elements) so as to address the above mentioned important aspects of bolted joint in crash simulations

Proposed modeling technique for the Bolt joint representation

Approach 1: Bolted joint modeling with beam element

Refer Figure 2 where bolted joint between two plates is modeled. The bolt shank is modeled with beam element (component 3) and its connection to surrounding plate is made through discrete spring elements which act only in local compression (component 4). The bolt head and nut is modeled with rigid shells (component 5 and 6).

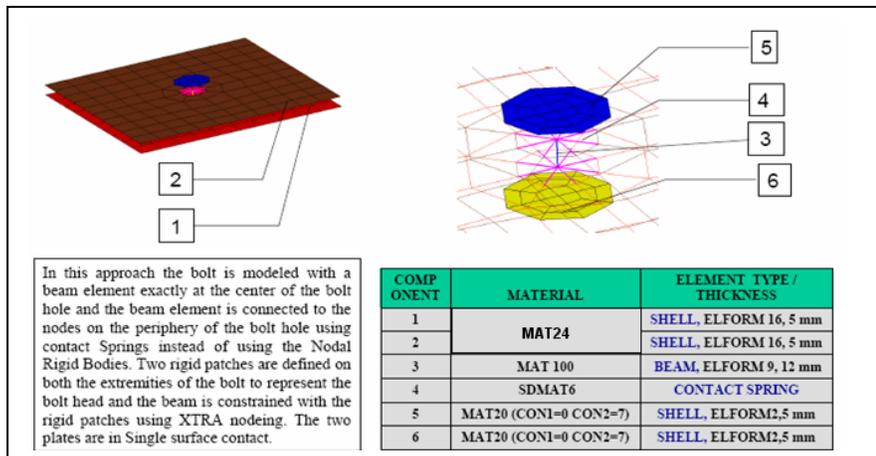


Figure 2-1D Beam with discrete spring

Pre-stress is applied to bolt beam using *INITIAL_AXIAL_FORCE_BEAM card. To model the failure of the bolt, force based or stress based failure criteria as suggested by LS-DYNA 971 R3 can be used.

Approach 2: Bolted joint modeling with solid elements.

In this method alternative bolt modeling approach is proposed wherein bolt shank is modeled with solid elements rather than beam and discrete springs approach discussed earlier.

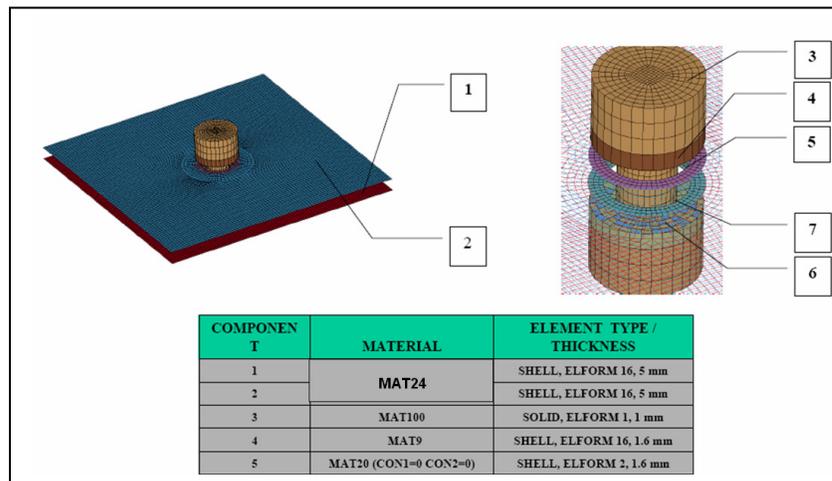


Figure 3- Hex solid element Bolt with appropriate contact

In this approach interactions between the bolt shank and clamping plates can be simulated through contact interactions and not through fixed discrete springs. (Refer **Figure 3**) Pre stress can be introduced to solid bolt using *INITIAL_STRESS_SECTION card. In this approach bolt failure can be initiated through plastic strain.

Validation of proposed bolt model against theoretical calculations

Following tests were simulated with proposed bolt modeling techniques and simulation results are validated against theoretical predictions.

- Shear test to validate interaction between shank and plates.
- Compression and tension test to validate pre-stress/pre-loading in bolt.
- To validate friction force between bolt head and clamped plates additional test of sliding of bolt (modeled with hexa solid elements) is simulated on the clamped plate.

Shear test for bolted joint–The objective of this test is to validate the proposed bolt model to simulate the contact interactions between bolt shank and surrounding plates (bearing load) under shear loads. **Figure 4** shows that two plates are connected using bolted joint represented by beam elements and contact springs definitions. No pre-stress is considered for this test. The load is applied in Shear direction as shown in **Figure 5**. The same test is also used to validate bolt model with solid elements.

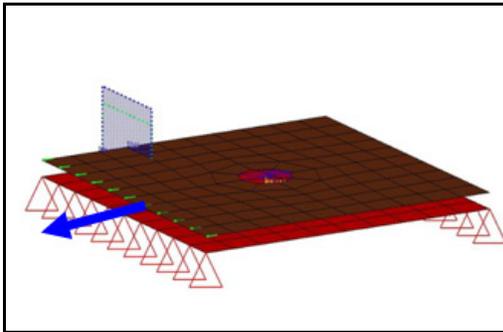


Figure 4 - Shear test model

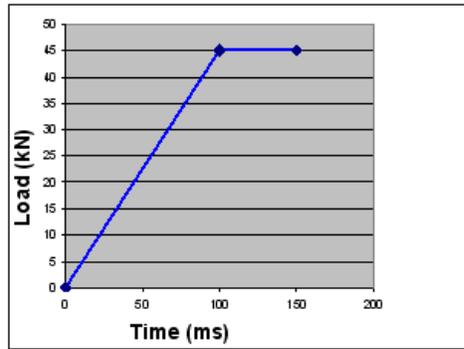


Figure 5 - Applied Load in shear direction

Shear test for bolted joint - simulation results -Beam model results (Refer **Figure 6**) shows that bearing stresses predicted are located in the area of contact highlighted by circle. Stress pattern obtained by this methodology closely agree with realistic physical behavior which is otherwise not possible to capture by conventional bolt modeling with beam and spider (rigid link) arrangement. **Figure 7** shows bolt forces in shear direction reaches to applied load value of 45 KN which matches closely with applied load curve shown in **Figure 5**. The Bolt modeling with solid hex elements also show similar results.

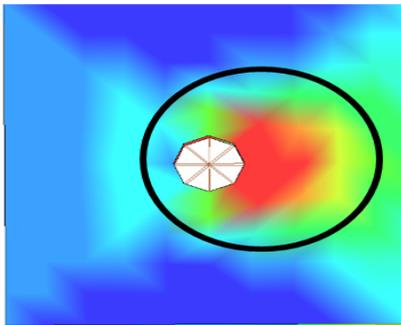


Figure 6 – Von-Mises stress

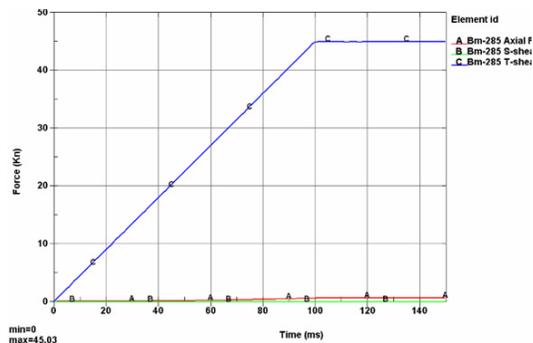


Figure 7 - Bolt forces reaction forces

Tension/compression test for bolted joint: The objective of this test is to validate the proposed bolt model to represent the bolt pre-load (pre-stress in the bolt) in crash simulations. As shown in **Figure 8** bolted joint modeled with beam element is subjected to axial tension and compression loads. Bolt pre-load during bolt tightening for the bolted joint is shown in **Figure 8**. To validate the model in axial test conditions, the known axial force is applied to the assembly after the pre-stressing (bolt tightening) is done (refer **Figure 8**). The same test is also used to validate bolt model with solid elements.

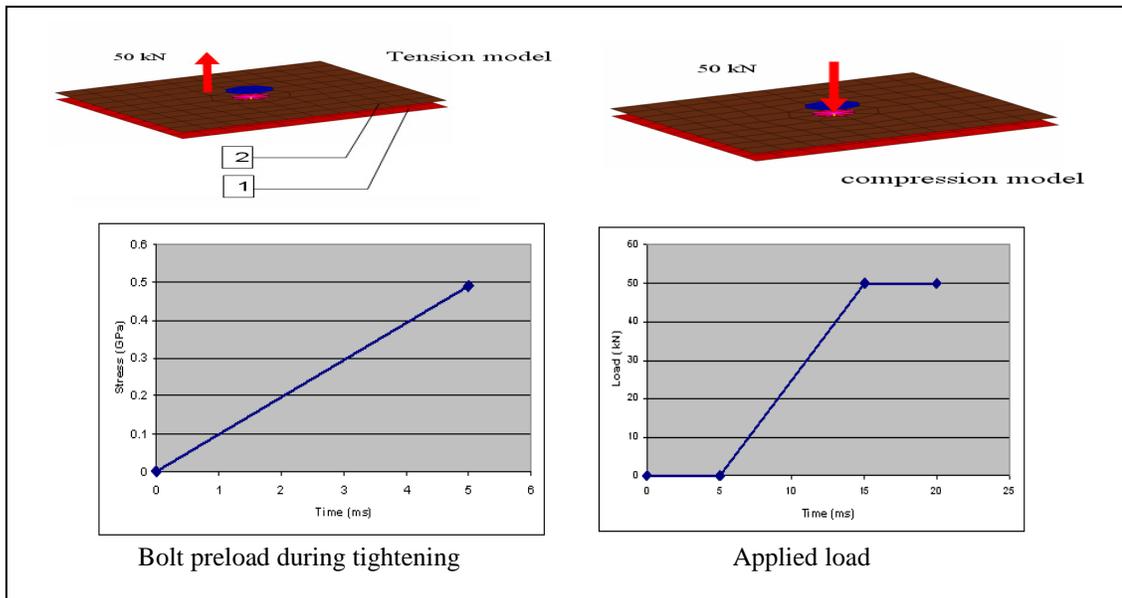


Figure 8 –Test set up for bolt tension/compression test with applied pre-load and prescribed force

Tension/compression test for bolted joint simulation results: Figure 9 shows that pre-load of magnitude of 36 KN is generated in +Z direction on shank at 5 ms shown by red color. At 5 ms tensile load in +ve Z direction is acting on the plates. From 5 ms till 12 ms the clamping load is overcome by the applied load. From 12 ms till 15ms increase in tensile axial load has been seen till it reaches to 50 KN. The behavior shown by beam model confirms closely with the theoretical calculation. Similar behavior which matches with theoretical predictions is observed in case of compression test. The Bolt modeling with solid hex elements also show similar results under these two tests scenario (Approach2)

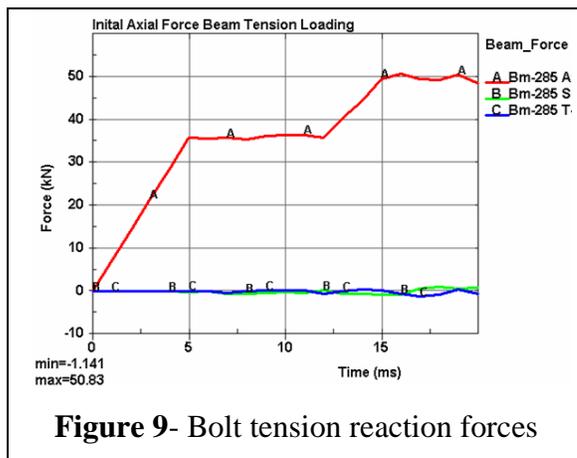


Figure 9- Bolt tension reaction forces

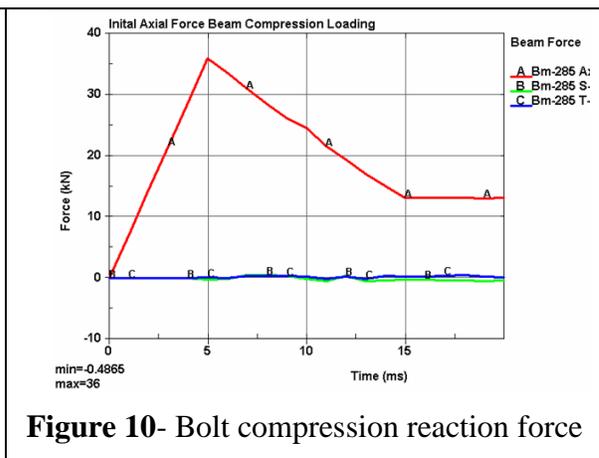


Figure 10- Bolt compression reaction force

Sliding test for bolted joints- The objective of this test is to validate the frictional forces between bolt head/nut and clamping plates. This is done by sliding the bolt on clamping plates as shown in Figure 11. In this case prescribed motion is applied to the bolt and contact forces are

recorded as frictional forces and same is compared with theoretical values expected. In this model during first 5ms the pre-stress is applied as shown in **Figure 11**. Top plate i.e. plate number 3 is subjected to prescribed motion as shown in **Figure 11**. Based on engineering judgment, static frictional co-efficient value of 0.3 is used in contact algorithm. Beam element with discrete spring (approach 1) is not suitable to simulate the sliding.

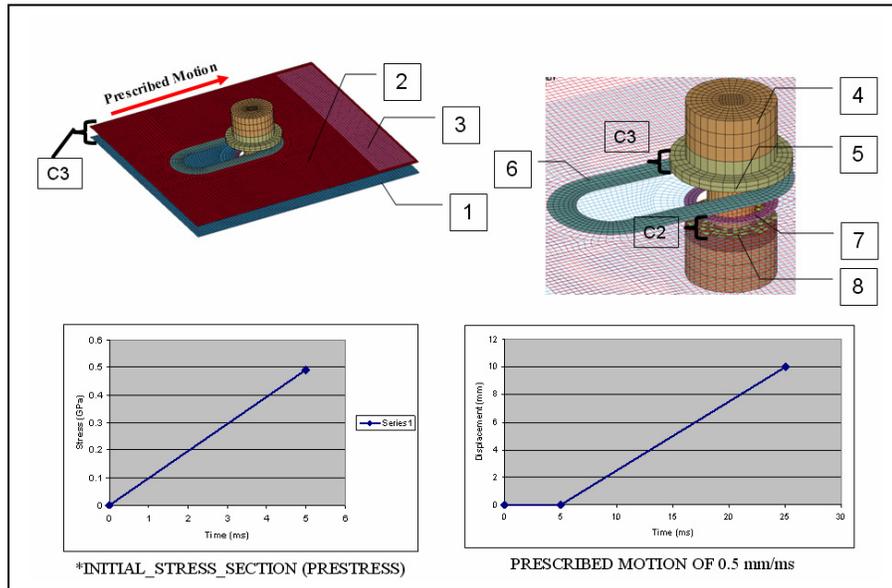


Figure 11 –Test set up for sliding test with applied pre-load and prescribed motion

Sliding test for bolted joint simulation results -The simulation results for sliding test are shown in **Figure 12**. The red color curve show the variation of bolt pre-load during the sliding and the green curve is the contact forces tapped which represent the frictional force. Since coefficient of friction is defined as 0.3 the expected frictional force values is 30 % of defined preload 36 KN. The green curve show that 10.70 KN frictional force is predicted which matches well with theoretical prediction. Hence the proposed bolt model well predicts the frictional forces in the bolted joint.

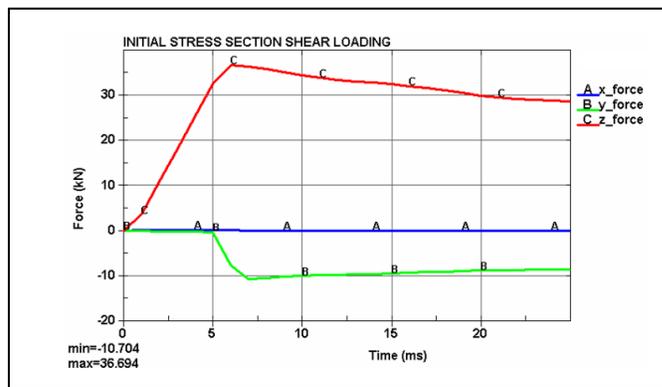


Figure 12- Forces shank and plates

Validation of proposed bolt model against experimental results

To validate the above modeling approach experimental tests were conducted wherein bolted joint was tested under tension loading and shear loading. The same test conditions were simulated in LS-DYNA with help of bolt modeling approaches discussed earlier. The comparison of simulation results predicted and test results is discussed in this session.

Tension loading of bolt joint –Tension test setup is shown in the **Figure 13**. During the tension testing initially M8 bolt with 8.8 property class was tightened with 23 N-m torque and bolted connection was established. This bolt joint assembly was further loaded with tensile loads until failure of bolt joint was observed.

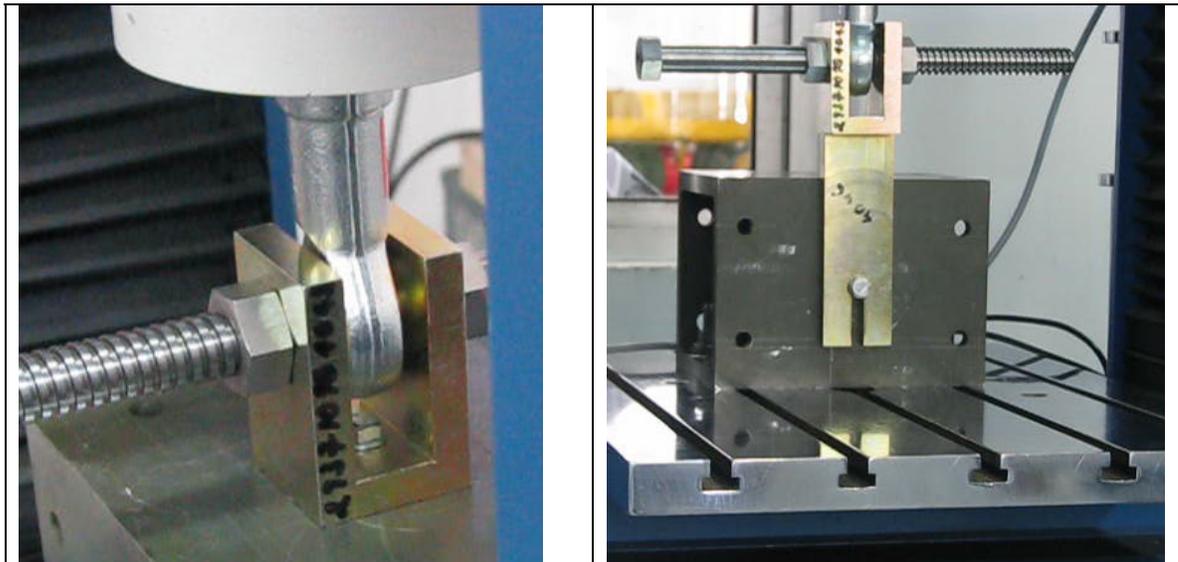


Figure 13 : Tension and sliding test set up for bolted joint testing

Sliding testing of bolted joint: Sliding/shear test is also carried on the bolted joint assembly to correlate the frictional and shear loading behavior of bolt joint assembly. The test set up for sliding testing is shown in **Figure 13**. The bolt tightening torque of 22 N-m was used during the test. It is being observed that plate started sliding when 3 KN force was reached on UTM. The tightening torque of 22 N-m approx. creates 10 KN clamping loads on the plate. Assuming 0.3 coefficient of friction, plate is expected to start sliding when 3 KN force is reached which is being observed in the test. During the FE simulations for this test coefficient of friction of 0.3 was used.

Comparison of simulation predictions with test results

Tension test results - **Figure 14** shows forces Vs displacement curve tapped from physical test and FE model. Black colored curve is force Vs displacement curve tapped from physical test while blue and red colored curves are force Vs displacement curve tapped from FE model. The maximum force obtained in physical test is 32 KN before failure whereas simulation predicts 28KN. No failure criterion was defined for bolt in simulation. Thus the proposed bolt modeling methodology using LS-DYNA reasonably predicts the real life behavior of the bolt under tensile

loading conditions. It is observed that physical test results show softer response in elastic region compared to CAE predictions.

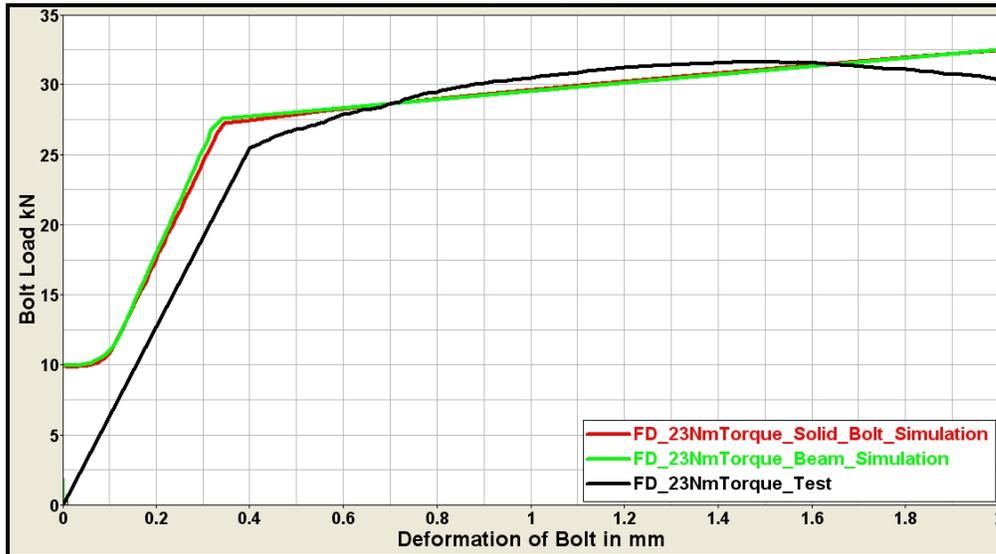


Figure 14 - Forces Vs displacement tapped from physical test and FEM model for tension test

Bolt sliding test results -Figure 15 shows forces Vs displacement curve tapped from physical test and FE model for sliding test of bolted joint. Black colored curve is physical test result while blue and red colored curves are force Vs displacement curve tapped from FE model. The maximum sliding force obtained in physical test is 3 KN whereas simulation predicts 2.8KN. Comparison of test results and simulation results show that the proposed bolt modeling methodology in LS-DYNA with pre-load definition reasonably predicts the physical behavior of bolted joint under shear loading.

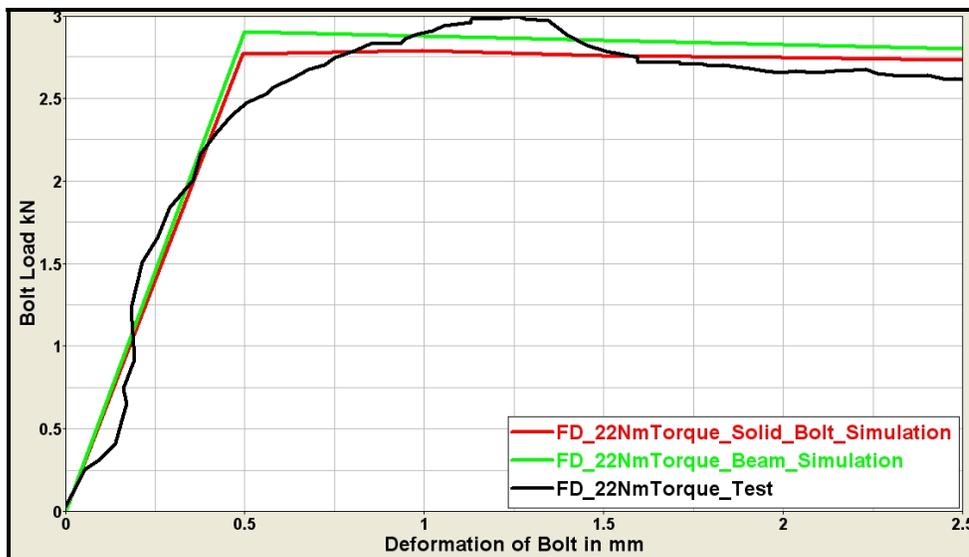


Figure 15 - Forces Vs displacement tapped from physical test and FEM model for sliding test

Conclusion

In the present paper attempt has been made to model the bolt pre-load and resulting bearing interactions between bolt shank and clamped plates for simulating realistic bolted joint behavior under tensile and shear loading conditions in CAE environment. Two bolt modeling approaches are discussed one with beam elements and other with solid hexa element modeling. Bolted joint behavior predicted by both the modeling approaches show good agreement with theoretical calculations and physical test results under shear and tensile loading conditions.

- Beam model is having an advantage of simulating the bolt failure if failure forces for bolted joint are known under different loading conditions.
- Solid element bolt model also can be used for failure prediction with the help of failure plastic strain definition provided reasonable mesh size is used for discretization bolt geometry. Solid model approach is also useful to simulate sliding displacement between bolt and clamped plates depending on the type of applications.

Further detailed study is required to be carried out with respect to bolt failure prediction under static and dynamic loadings that occurs in crash applications.

References

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