Jordan Journal of Civil Engineering, Volume **18**, No. **2**, **2024**
DOI: https://doi.org/10.14525/JJCE.v18i2.06

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Investigating the Effects of Adhesive on the Shear Capacity of Bolted Steel Connections

Bilal Yasin [1]***, Hatem Almasaeid*** [2]*****, Rabab Allouzi*** [3]***, Donia Salman*** [4]***,***
Khairedin Abdalla [5]***, Abdelmajeed Alkasassbeh*** [6]

[1] *Assistant Professor, Civil Engineering Department, Al al-Bayt University, Al-Mafraq 25113, Jordan. E-Mail: yasinbilal@aabu.edu.jo*
[2] *Assistant Professor, Civil Engineering Department, Al al-Bayt University, Al-Mafraq 25113, Jordan. * Corresponding Author. E-Mail: almasaeid.h@aabu.edu.jo)*
[3] *Professor, Department of Civil Engineering, University of Jordan, Amman 11942, Jordan. E-Mail: r.louzi@ju.edu.jo*
[4] *Research Assistant, Civil Engineering Department, University of Mississippi, MS 38655, USA. E-Mail: dgsalman@go.olemiss.edu*
[5] *Professor, Department of Civil Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan. E-Mail: abdalla@just.edu.jo*
[6] *Assistant Professor, Civil Engineering Department, Al al-Bayt University, Al-Mafraq 25113, Jordan. E-Mail: abdelmajeed-k@aabu.edu.jo*

ARTICLE INFO

Article History:
Received: 23/11/2023
Accepted: 24/2/2024

ABSTRACT

Recently, there has been a particular emphasis on the use of structural adhesives in steel connection systems. Applying adhesives that possess both high strength and flexibility would be highly advantageous for structural purposes. In this study, experimental tests are conducted on two main different types of steel-plate connections; namely, bolted connections and bolted connections with glue. The number of bolts ranged from one to eight for each connection type, such that a total of seven specimens of each type are tested. Additionally, one specimen with only glue is also tested for comparison. The findings indicated that the inclusion of up to four bolts with glue along the connection does not significantly increase the ultimate stress. This can be attributed to the non-uniform distribution of normal stresses, induced by the tightening of the small number of bolts that are not arranged across the entire connection region, on the capacity of the connection in the perpendicular direction. Thus, the connection could have been adequately established the same capacity through the use of adhesive alone. In contrast, the capacity is increased up to 60% and 100% when six or eight bolts are added, respectively, compared to the use of the connection with glue only. A three-dimensional finite-element analysis is developed based on the tested connections using ABAQUS/Explicit software. The glued interface between two steel plates is modelled using cohesive and damage criteria. The results are demonstrated to be consistent with the experimental findings.

Keywords: ABAQUS, Adhesive, Bolts, Finite-element analysis, Shear, Steel connections.

INTRODUCTION

Bolt connections are a common type of connection. They involve the use of bolts, nuts and washers to clamp two or more structural components together in such a way as to enable loads to be transferred between them. Bolt connections have various advantages over other types of connection, including ease of installation and disassembly, the capacity to handle changing loads and tolerances and the capacity to provide a high level of rigidity and strength. Nevertheless, bolt connections must be properly constructed to ensure that they will be able to withstand the loads and strains that they will be subjected to throughout their lifetime. As such, careful consideration should be given to the material, size and spacing of the bolts, as well as the component design. The fundamental design of a bolt connection involves drilling holes through the components that are to be joined and inserting bolts through these holes. A torque wrench, nuts and washers are then used to tighten the bolts to the necessary torque. The clamping force generated by the bolts and nuts provides the frictional force that keeps the components together and enables them to transfer loads.

A typical bolt assembly was carried out under tension alone. Under these conditions, thread stripping was the common cause of failure for thread stripping-type components. When the same bolt assembly was subjected to combined tension and bending, however, the failure mode switched to fracture of the threaded section of the bolt shank (Chesoan et al., 2020; Plaitano et al., 2020; Tartaglia & D'Aniello, 2021). It is common for bolted connections, such as T-stub connections or end plate connections, to exhibit mixed shear and axial behavior (Iannone et al., 2011; Latour & Rizzano, 2012; Latour et al., 2018; Nastri & Plaitano, 2022). In such instances, it has been found that the primary cause of failure is the axial tensile stress, even though the bending component cannot be ignored for high displacements. A similar issue is seen in replacement link connections, where the bolts experience significant deformations.

Montgomery (2008) conducted a detailed exploration of the methodologies employed in bolt simulations, with a particular emphasis on the impact of boundary conditions and software settings. The research utilized a fully-detailed simulated threaded bolt as the baseline model. This was then analyzed against two other models: one that incorporated interaction at the threaded region and another that employed a tied contact approach at the same region. This comparative approach provided valuable insights into the relative performance and accuracy of different simulation strategies in the context of bolt modeling. Silva (2009) employed a numerical model using the finite-element (FE) method. This model was developed in ANSYS Parametric Design Language within the ANSYS 10.0 software. The mesh for the connection consisted of 20-node 3D elements. To assess the fatigue strength of the riveted and bolted connections, surface-to-surface contact pairs were established between various components and different friction coefficients were employed. The comparison was made through both experimental tests and numerical simulations. Rodrigues et al. (2017) investigated the behavior of standard bolted steel connections under the influence of monotonic loads, employing numerical models for their analysis. Methodologies based on FE analysis were proposed for double shear-bolted connections. In addition, the non-linear behavior of the connections was investigated and their performances were compared. The numerical modeling of the bolted connections and the linear elastic and elastoplastic analyses revealed the presence of two slip levels associated with local non-linearities caused by the contact pairs, which varied with the clamping stress. The focus shifted to the prediction of fatigue strength in riveted connections using the FE model in a study performed by Correia et al. (2017). In this case, two alternative FE models were proposed; one based on solid FE with contact elements to simulate component contact and the other using shell FE to model the plates of the riveted connection. Through a comparison of crack initiation and crack propagation, the study demonstrated the effectiveness of the two-stage model in yielding consistent results. Also, this research highlighted the significance of computational tools in evaluating the fatigue behavior of riveted connections, providing valuable insights into the design and maintenance of ancient metallic bridges. Abdel-Jaber et al. (2020) conducted a full-scale study to investigate the behavior of a tubular and fitting scaffolding system subjected to lateral and vertical loads. Experimental and theoretical calculations were carried out to determine the moment-rotation capacities of three common connections: sleeve couplers, swivel couplers and right-angle couplers. The results showed that the cyclic loads had a significant effect on the moment-rotation capacity of the connections. An FE analysis was further conducted using ABAQUS software and the results were comparable to the experimental findings. Plaitano et al. (2022) presented a simplified approach to model the failure behavior of high-strength bolts under combined tension and bending. The authors proposed a new failure criterion based on the maximum principal stress theory, which considers the effects of both tension and bending on the bolt. Moreover, it allows for the reduction of computational time.

The concept of utilizing adhesives for the bonding of metals can be traced back to the modification of phenolic adhesives, which were initially employed for the bonding of wood as well as the implementation of rubber-metal joints in machinery (Piekarczyk & Grec, 2012). A diverse range of adhesives exhibiting distinct carrying and deformation characteristics, together with various handling properties, are available for the design of bonded structures. The task of selecting the appropriate adhesive system poses a challenge in civil engineering due to a prevalent lack of experience in this domain. The overall specifications of an adhesive are defined by a particular viscosity during the production process and an adequate ability to carry and deform the bonded surface. Notwithstanding these parameters, the characteristics of the surface to which the compound adheres play a significant role. The application of adhesive connections in civil engineering and building industry has attracted increasing attention in recent years (Kumar et al., 2017). Certain applications of structural adhesives have significant importance, including-but not limited to-the reinforcement of pre-existing concrete elements (Giurgiutiu et al., 2001; Ali et al., 2005; Pandulu et al., 2020), hybrid composite-concrete beams (Verbruggen et al., 2016) and adhesive anchors (Marcon et al., 2017). Adhesive connections have also been used in steel-concrete joints and several studies have been performed to assess the shear strength of adhesive joints in steel-concrete composite systems (Berthet et al., 2011; Helincks et al., 2013; Meaud et al, 2014; Zhan et al., 2016). Moreover, non-destructive evaluations and early-stage damage detection using the phenomenon of elastic wave propagation have been conducted to characterize the contact between adhesive-connected components (Rokhlin, 1991; di Scalea et al., 2001; Yonathan et al., 2017). On the other hand, the stress distribution along the connection contact area depends on the mechanical properties of the adhesive and the geometry of the joint (da Silva et al., 2005; Petrie, 2007). Significant stress concentrations in adhesive joints can be avoided by applying a relatively low-elasticity ductile glue. Compared to rigid adhesives, flexible adhesives generally have low strength, but can distribute stress evenly over the connection area. This is because rigid adhesives are unable to redistribute the stress concentrations at the ends of the overlap (da Silva & Campilho, 2015). The use of relatively strong and flexible adhesives would be ideal for structural applications (Pravdová et al., 2016; Machalická et al., 2016).

Ciupacka et al. (2017) discussed the bonding in steel constructions and highlighted the importance of cleaning and degreasing the steel surfaces before the elements are bonded together. Mechanical pre-treatments, such as blasting, were also recommended to improve the adhesion properties. The study emphasized that the type of loading has a significant impact on the carrying capacity of the bonded connection. Uneven and combined loads, as well as peel stresses, should be avoided, while uniformly distributed tension, pressure and shear impacts are considered as suitable. The paper also mentioned that slopping the adherent ends can help reduce stress peaks and increase the carrying capacity of the bonded connection. The study also involved the determination of a suitable loading cycle for bonded joints in steel constructions. This was done based on statistical studies using an hourly approach.

Since bolts are one of the most stressed components of connections, it is essential to analyze their performance and predict the failure of the connection in advance. In addition, careful attention must be paid to the contact between the adhesive-connected components. The FE method is a useful technique for analyzing the behavior of structural assemblies that are subjected to different activities. In fact, FE models enable the visualization of the distribution of stress, plastic deformation, contact damage, cracks, … etc. related to the creation of tests, hence facilitating the interpretation of the function of each component of the system. To achieve a sufficient level of accuracy, however, it is essential to model the geometry and material properties to mimic the actual behavior of the structural assembly during the testing. ABAQUS software allows for the modeling of complex interactions, such as the contact and frictional effects, between the bolts and the surrounding materials. This study investigates three distinct types of connection: bolted connections, glued connections and a combination of both systems (glued and bolted connections). The connections are both experimentally tested and numerically modelled using ABAQUS software. The research is aimed at examining the impact of the glue and bolts separately, as well as the combined effect of both in the connection, to enable comparisons of the systems to be made. Also, for scenarios where the addition of bolts is impractical, the feasibility of enhancing the connection capacity through the application of glue is examined. Furthermore, there are limitations provided by the codes for the distance between bolts such that it is sometimes hard to add more to the connection.

MATERIALS AND METHODS

Materials

In this study, NitoMortar TC2000 epoxy resin was used in adhering the steel plates. Table 1 lists the characteristics of the used adhesive. In addition, Figure 1 and Table 2 show the experimentally obtained stress-strain curve of the steel plates and the characteristics of the bolts used in this study, respectively. The details for the epoxy and bolts specified in Table 1 and Table 2 were obtained from the materials datasheet provided by the manufacturer.

Table 1. NitoMortar TC2000 epoxy resin properties

Property	Value	Note
Compressive strength	90 MPa	@ 7 Days
Flexural strength	19 MPa	@ 7 Days
Tensile strength	18 MPa	@ 7 Days

* As provided by the supplier.

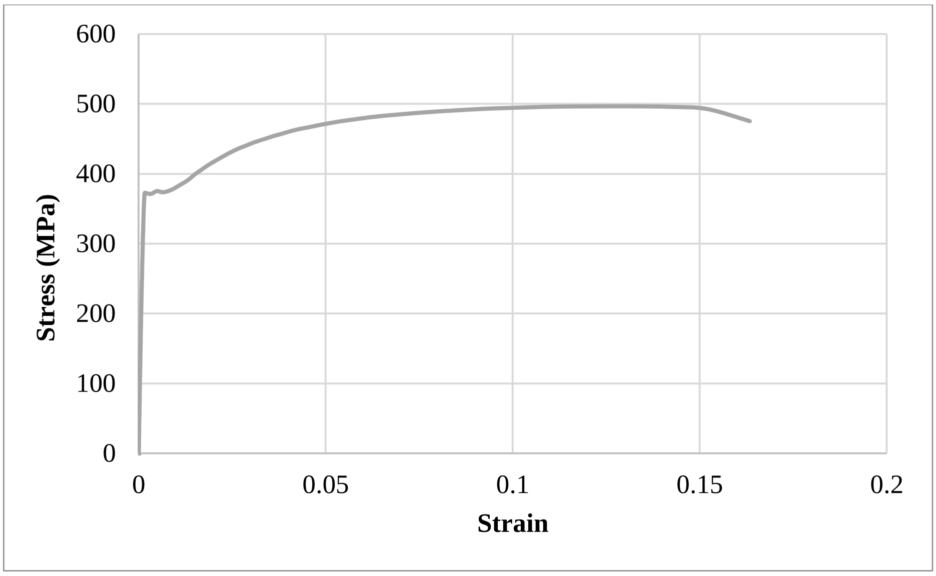


Figure (1): Steel plates' stress-strain curve

Table 2. Bolts' characteristics

Property	Value
Bolt size	M6
Bolt diameter	6 mm
Tensile stress	800 MPa
Torque	9.4 N.m
Hardness	22-32
Elongation	12 %

Test Specimens

Fifteen 400*100*10 mm steel-plate connections were tested in this study. The plates were connected to each other by bolts, adhesive or by both together. Figure 2 shows the details of the steel-plate connections.

Sample Preparation

The steel connections were prepared as follows:

a. Bolted connections:

The bolts were pre-tensioned with a 1N force.

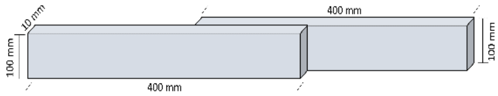
b. Connections with adhesive:

To assemble the connection, the adhesive layer was uniformly spread upon 100*100mm on one of the steel plates. Then, the other plate was mounted and compressed while maintaining a layer of 10-mm thickness of the adhesive. The connection was left to cure for 7 days.

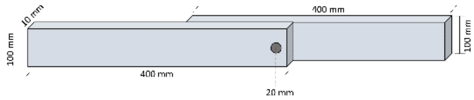
c. Bolted connections with adhesion:

An adhesive layer was uniformly spread upon 100*100 mm on one of the steel plates. Then, the other plate was mounted and the bolts were added and pre-tensioned with a 1N force while maintaining a layer of 10-mm thickness of the adhesive. The connection was left to cure for 7 days.

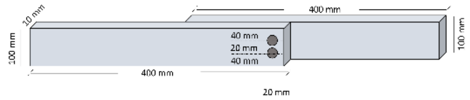
For all samples, the surface of each steel plate was cleaned using alcohol without any surface-treatment procedures.



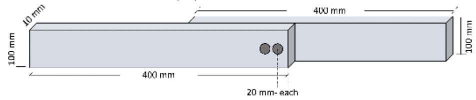
(a) Glued connection



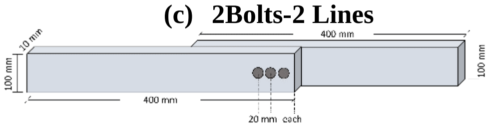
(b) 1Bolt-1 Line



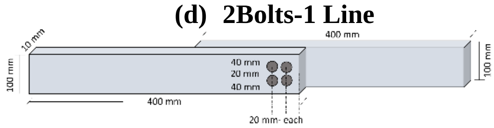
(c) 2Bolts-2 Lines



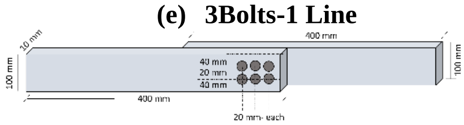
(d) 2Bolts-1 Line



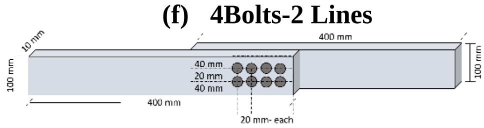
(e) 3Bolts-1 Line



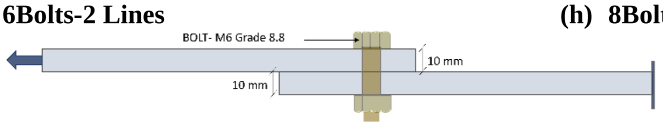
(f) 4Bolts-2 Lines



(g) 6Bolts-2 Lines



(h) 8Bolts-2 Lines



(i) Section in plate with one bolt connection

Figure (2): Details of steel-plate connections

Testing Setup

The experimental procedure includes a direct tension of the steel plates until rupture. For each connection, the testing machine exports a load-elongation curve. The testing machine and setup are shown in Figure 3.

Figure (3): Testing setup

RESULTS

Figure 4 illustrates the test results for all the steel connections. Each result was an average of two or three connections with the same characteristics. The specimens were divided into three categories, according to the type of connection. For specimens that were connected with bolts only, the results showed that increasing the number of bolts resulted in an increase in the ultimate load at rupture linearly from 8 kN for one bolt to 68 kN for eight bolts. It was also clear that the capacity obtained for the bolts was almost equal to the capacity of one bolt; i.e., 8 kN, multiplied by the number of bolts. Additionally, it was observed that the bolts of the bolted connections ruptured and failed due to shear stress. On the other hand, the ultimate load at rupture for the connection assembled using only adhesive was 47 kN. The addition of up to 4 bolts along with the adhesive did not increase the ultimate load of the specimen with adhesive only, such that all the capacities were less than or almost equal to 47 kN. Also, the addition of up to four bolts to certain connections in some specimens had an adverse effect and the results of some specimens showed odd behavior compared to their counterparts. This was due to the capacity of the adhesive to evenly distribute the stresses along the overlap (Bedon et al., 2018). However, when up to four bolts were introduced, the stresses were not properly distributed across all the surfaces, leading to an uneven distribution of normal stresses over the contact region between the plates in the perpendicular direction. Thus, there was no increase in the capacity of the system with this addition of bolts.

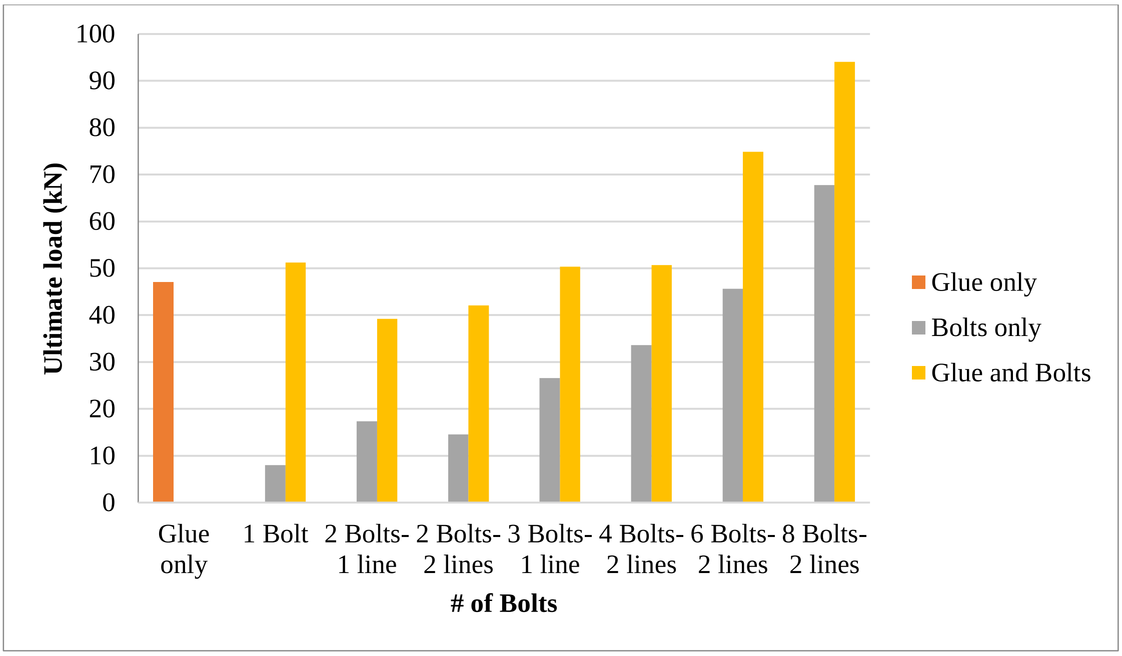


Figure (4): Connections' testing results

On the contrary, the addition of six bolts on two lines together with the glue provided an ultimate load of 75kN, showing a 60% increase compared to the specimen where only adhesive was used. Furthermore, the ultimate load of 46 kN achieved with six bolts alone was nearly identical to that of the specimen containing only glue. Therefore, it was recommended that either the system with glue only or six bolts distributed along two lines be used to achieve this specific ultimate-load value. For the specimens with eight bolts on two lines with the presence of adhesive, an ultimate-load value of 94 kN was reached, showing a 100% increase in the ultimate load in comparison to the specimen with glue alone. These findings showed that the addition of at least six bolts together with the glue increased the area where the bolts were distributed along the plate, resulting in a more even distribution of normal stresses. Therefore, both the bolts and the glue systems worked together to notably increase the capacity of the entire connection. Thus, the use of such a system of bolts and glue in combination can be beneficial in areas where it is hard or impractical to add more bolts. Also, because of the limitations of the spacing between bolts, glue can be used instead. To summarize, the use of a system of connections consisting entirely of glue was adequate to achieve a bond capacity of 40 kN. The addition of up to four bolts to the system did not result in an improvement in the ultimate-bond strength, probably because of the uneven distribution of stress. Nevertheless, the addition of six or eight bolts to the glue system significantly enhanced the ultimate-bond capacity of the system, enabling it to reach 70 kN and 90 kN, respectively. It was noticed that the bolts in the specimens comprised of both bolts and glue also ruptured due to shear. Furthermore, no fracture was observed in the steel plates of all the specimens. There were only stress concentrations that caused strain deformation in the areas where the openings of the bolts were located. Moreover, it should be mentioned that a comparison of the failure between those specimens that had only bolts and those that had both bolts and glue revealed that there was no noticeable difference in the mode of failure. The only difference was in the maximum capacity that the connections were able to undertake. Figure 5 shows the failure in the tested connections and bolts.

Figure (5): Failure in bolts, glued plates and glued plates with bolts

Finite-element Modeling

Introduction

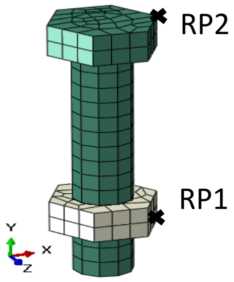
The three types of the tested connections; namely, glue-only, bolt-only and glued-and-bolted, were further numerically modeled using the Dynamic/Explicit FE analysis available by ABAQUS software.

Three-dimensional eight-node solid hexahedral continuum elements, C3D8R, were used along with reduced integration and hourglass-control methods to simulate all the components of the connections including the steel plates, bolts and nuts. Reduced integration was used as the lower order of its stiffness-creating integration can decrease the runtime, while the hourglass-control method was used to decrease any severe distortions to the mesh without excessively constraining the elements (ABAQUS, 6.14). The mesh size used for the steel plates for all connection types was 4 mm except through thickness, the steel plates were divided into three segments. Consequently, a mesh size of about 3.3 mm was obtained. Finer mesh was selected through the plate thickness to better transfer the stresses through thickness where the bolts/glue would come into contact in the connections. The mesh size for the bolts and nuts in the bolt-only and glued-and-bolted connections was considered as 2 mm. The mesh size of the bolts was chosen to be finer to sufficiently discretize the rounded geometry of the bolt. A mesh-sensitivity analysis was conducted to determine the sensitivity of response to the mesh-size and to adopt the above sizes to all three connection types.

An elastic-perfectly plastic material model was used to simulate the steel plates, bolts and nuts using the material properties as described in the experimental section, while the von Mises yield criterion was used to define the isotropic yield surface per ABAQUS 6.14. This surface was characterized by providing values of the uniaxial yield stress as a function of uniaxial equivalent plastic strain. For connections loaded monotonically to failure, an elasticity-perfectly plastic relationship was used.

Boundary Conditions and Loading

Similar to the experimental setup, a fixation was first applied to one of the steel plates from its side. A two-step analysis was defined for the bolt-only and glued-and-bolted steel-plate connections. A tightening axial force was applied to the bolt to represent the tightening torque that was applied to the bolt in the experimental setup. This boundary condition was imposed on the nut by making it a rigid body and applying an axial displacement at Reference Point 1 (RP1) along the bolt towards Reference Point 2 (RP2) (Figure 6). Then, a displacement-control procedure was applied to the other steel plate's edge to subject the connection to tension. Only the steel plate's edge fixation was applied in the first step and the displacement-control procedure was applied in the subsequent step for the connections of the glue-only steel-plate connection. Lastly, to prevent the heads of the bolts from distorting, they were modeled as rigid bodies and affixed to RP2 with the boundary conditions seen in Figure 6.



Reference Point	RP 1		RP 2	
Displacement	U1		U1	0
	U2		U2	0
	U3	1.5	U3	
Rotation	UR1		UR1	0
	UR2		UR2	0
	UR3		UR3	0

Figure (6): Positions of the reference points used to apply boundary conditions

Interfacial Modeling

The normal contact between the steel plates of the glue-only steel plates was defined as a hard-normal contact while a penalty technique was used to define its tangential contact and permit relative motion between the different surfaces at a coefficient of friction of 0.2. Meanwhile, a surface-to-surface contact was used to represent the glue material between the two surfaces of the steel plates while the traction *versus* separation rules were used to define its cohesive behavior along the contact zone. Damage contact was also defined to mimic the loss of cohesion and degradation that occurs at a cohesive interface in two stages: damage initiation and evolution. Equation (1) was used to define the damage-initiation phase in accordance with the maximum-stress criterion of the contact stress ratio (ABAQUS 6.14):

$$\left\{\frac{t_n}{t_n^o}, \frac{t_s}{t_s^o}, \frac{t_t}{t_t^o}\right\} = 1 \quad (1)$$

where, t_n, t_s and t_t are the nominal traction stress of the components and t_n^o, t_s^o and t_t^o are the peak values of the contact stress. The damage-initiation criterion was based on the maximal-stress criterion of the contact stress ratio which, in turn, depends on whether separation occurs perpendicular to the interfacial regions (i.e., tensile surface) or in the first or second shear direction of the plane. Once the criterion for damage initiation was met, a linear damage-evolution law was defined to represent the rate of degradation of the cohesion stiffness which, in turn, activates the friction model proportionally to it. The linear trend of the damage-evolution law was calibrated to mimic the results of the experimental setup, while the parameters for damage evolution were adjusted to determine the total plastic displacement, where through calibration, a value of 5 was selected.

The normal, tangential, cohesion and damage characteristics of the glued-and-bolted steel-plate connections were similar to that of the glue-only steel-plate connection, but with a total plastic displacement of 2. This is due to the effect of bolt tightening on the interface. Lastly, only the normal and tangential behaviors of the bolt-only steel-plate connection were specified similar to that of the glue-only steel plate connection.

Multiple studies have incorporated damage initiation and the evolution criteria in models to examine cohesive interfaces. Al-Chaar and Mehrabi (2008) used cohesive interfaces to numerically simulate the shear behavior of brick-to-frame and brick-to-brick mortar joints of infilled frames to determine their non-linear behavior. The interfacial model was able to effectively mimic the residual shearing and shearing, as well as the opening and closing of the joints under cyclic shearing loads of the experimental setup. Allouzi and Irfanoglu (2018) used a cohesive interface model with damage initiation and evolution behaviors to simulate the shear behavior of brick-to-frame and brick-to-brick mortar joints of walls made of reinforced concrete frames with masonry infill. The results of the simulation model were similar to that of the experimental results. The interfacial definition was also found to adequately simulate the behavior of the infilled frames under cyclic and monotonic loadings. Meanwhile, Abendeh et al. (2022) used the cohesive interface model of ABAQUS to simulate the cohesive interface between concrete infills and the steel tubes of concrete-filled steel tubes (CFSTs) under push-out loadings. The damage initiation was defined similar to Equation (1); an exponential-damage evolution was used to represent the rate of degradation of cohesion stiffness and a calibration was conducted to determine the exponential parameter. The proposed model was able to accurately capture the bond-slip behavior of the CFSTs under push-out loadings. Allouzi et al. (2022) proposed an artificial neural network (ANN) model to predict the entire interfacial behavior, as well as the initial and post-peak behaviors of circular and squared CFSTs under push-out loadings. The applicability of the proposed ANN model to numerical non-linear FE models was also examined to determine the performance of the CFSTs under axial loading. The proposed ANN method was used to construct models in ABAQUS to examine the cohesion damage criterion and damage. The models were found to be efficient and could simulate CFST columns under axial loads.

Finite-element Results

Figures 7, 8 and 9 present the results of the load-displacement curves of glue-only, bolt-only and glued-and-bolted steel-plate connections, respectively. The FE modeling results were in good agreement with the experimental results. Figure 10 depicts the von Mises stress distribution calculated in bolts in the bolt-only steel-plate connection at failure load. The figures indicate that a failure occurred in the bolts. The von Mises stress of bolts in the bolt-only and glued-and-bolted steel plate connections at the maximum load also indicated a failure in the bolts.

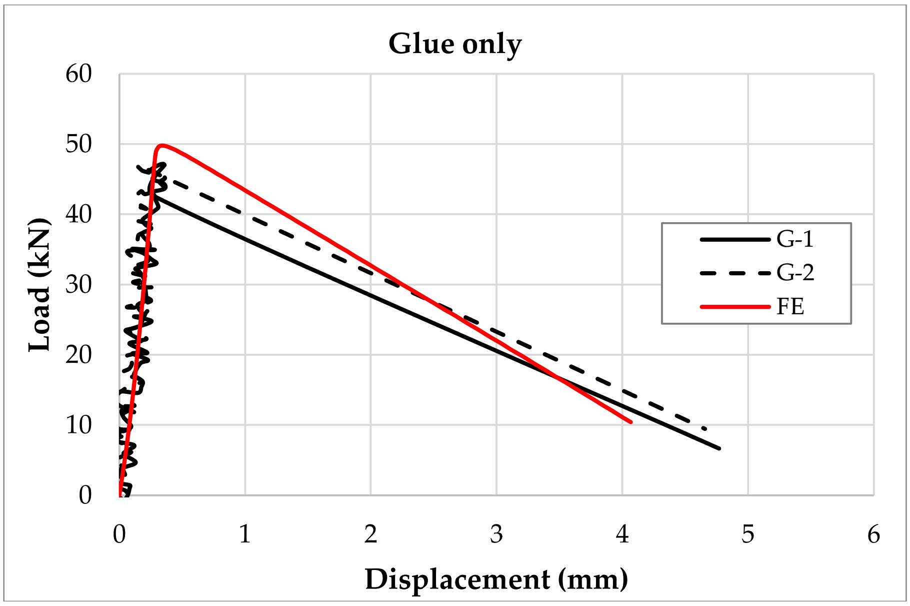


Figure (7): Load-displacement curve of the glue-only connection

Mesh-sensitivity Analysis

The sensitivity of the FE modeling results to the input parameters must be examined to validate the model and its outcomes. Therefore, this present study investigated the effect of input parameters related to mesh; namely, the mesh sizes of the steel plate and bolt.

A mesh-convergence study was performed on all the components of the six glued-and-bolted steel-plate connections that had been modeled using five different mesh sizes; namely 6, 5, 4, 3 and 2 mm of hexagonal (HEX) shape. As the steel plates were divided into three segments through their thickness, its mesh size was always considered as 3.33 mm. Figure 11 depicts the results of a load-displacement analysis of the six glued-and-bolted steel-plate connections modeled using five different mesh sizes. The results indicate that mesh size has a little effect on the response curve and the maximum load value. As such, all the bolts and steel-plate connections of this present study were modeled using mesh sizes of 2 mm and 4 mm, respectively.

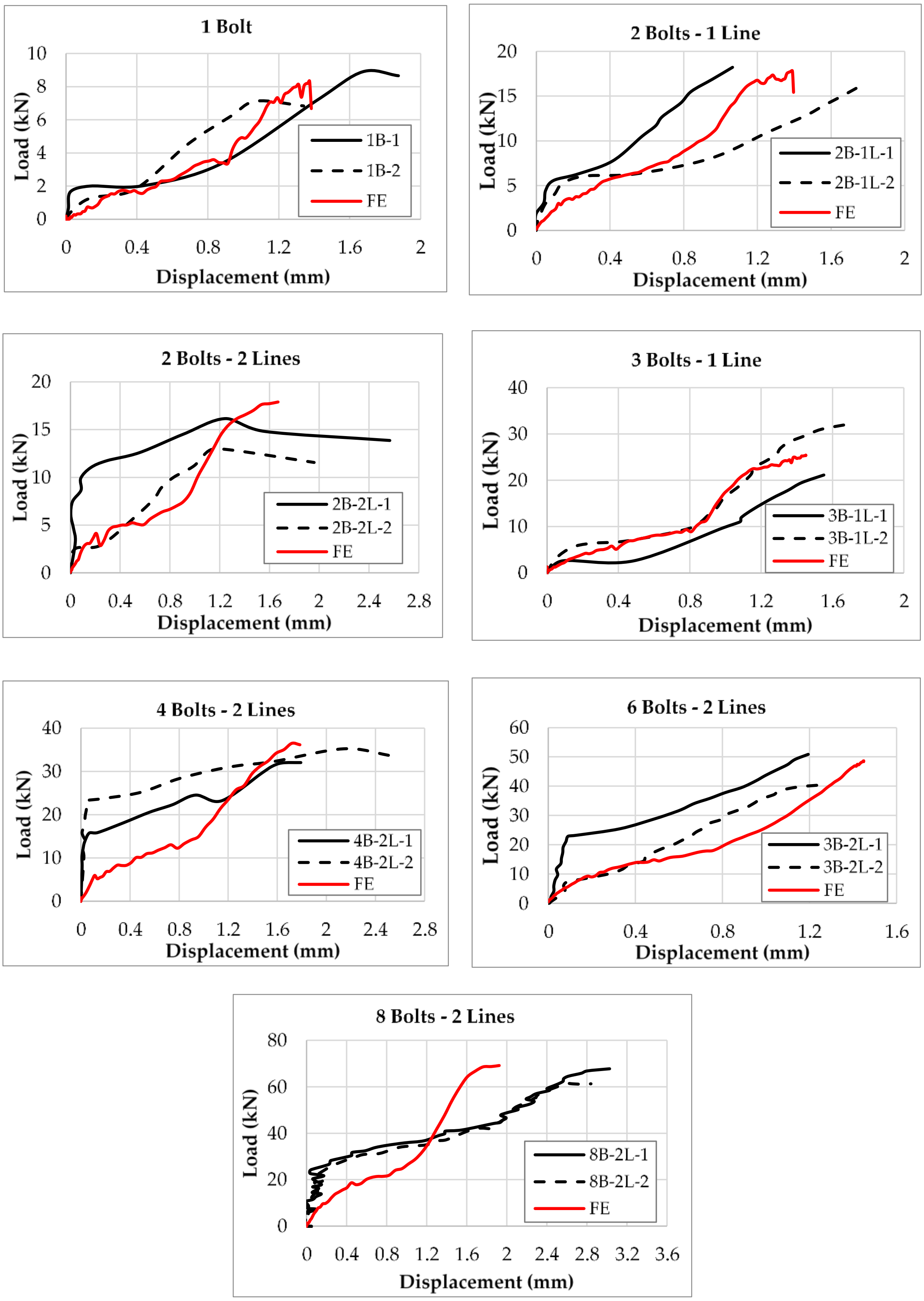


Figure (8): Load-displacement curve of the bolt-only connection

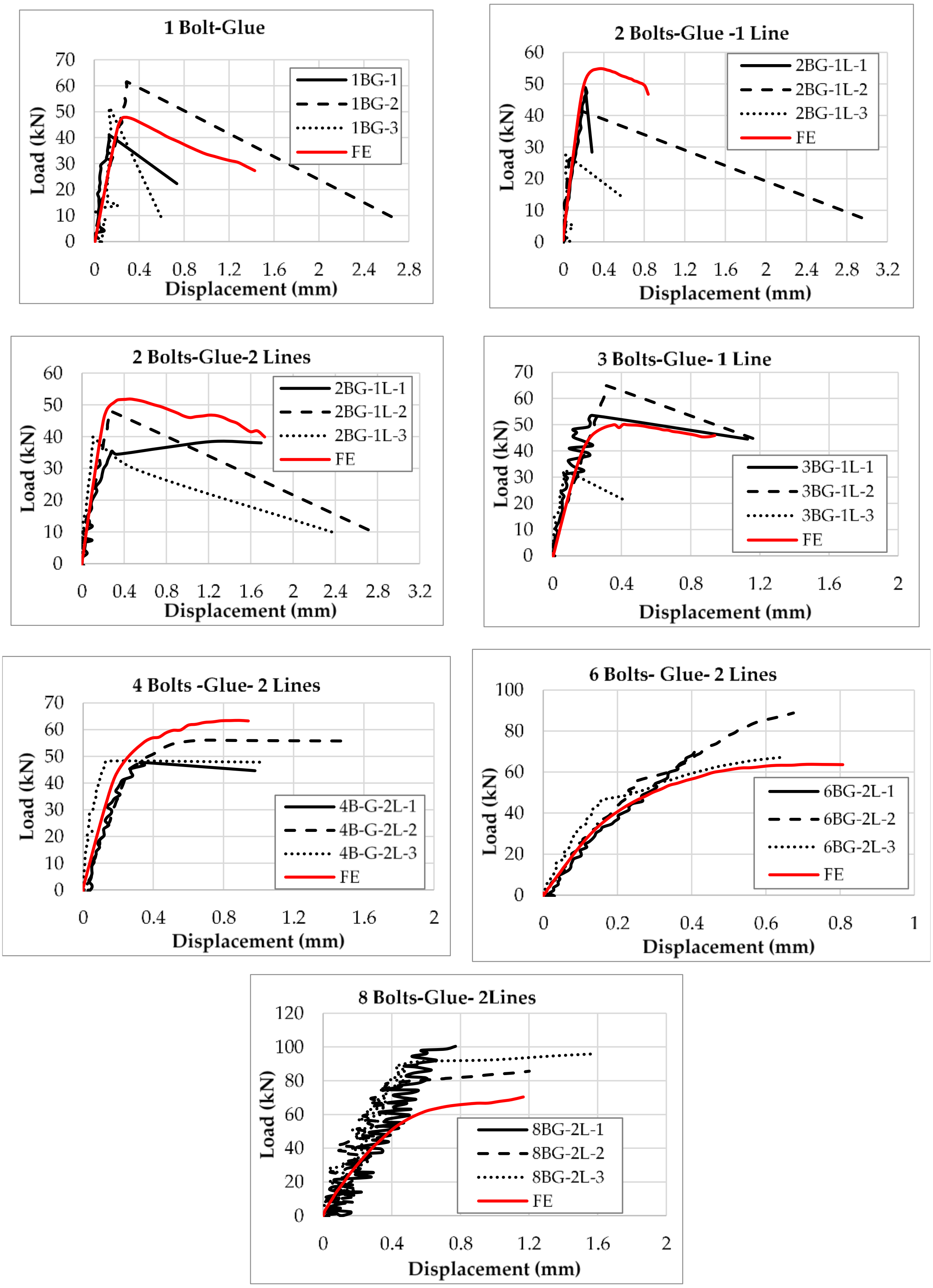


Figure (9): Load-displacement curve of the glued-and-bolted connection

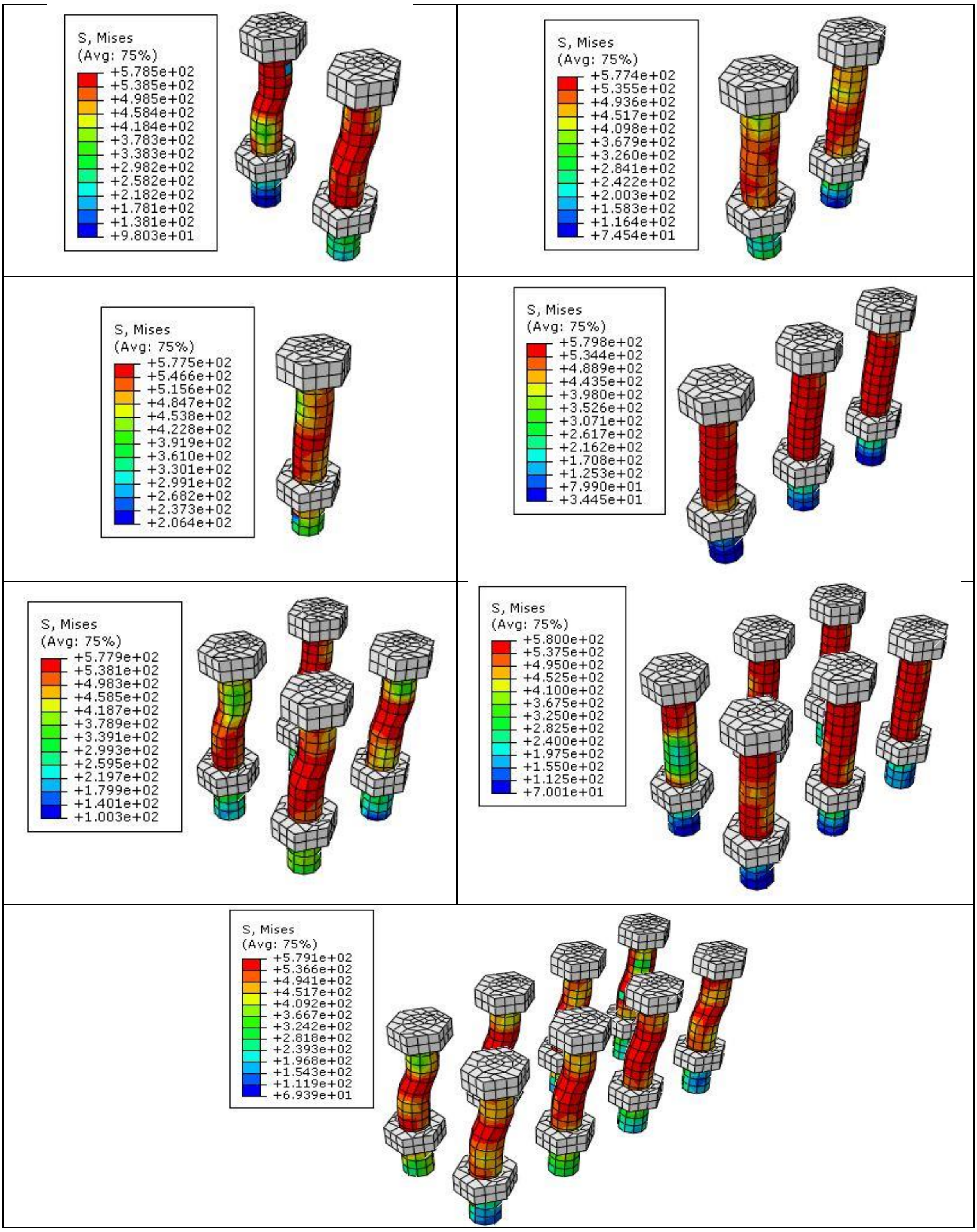


Figure (10): Von-Mises stresses at failure in the bolts of the bolt-only connection

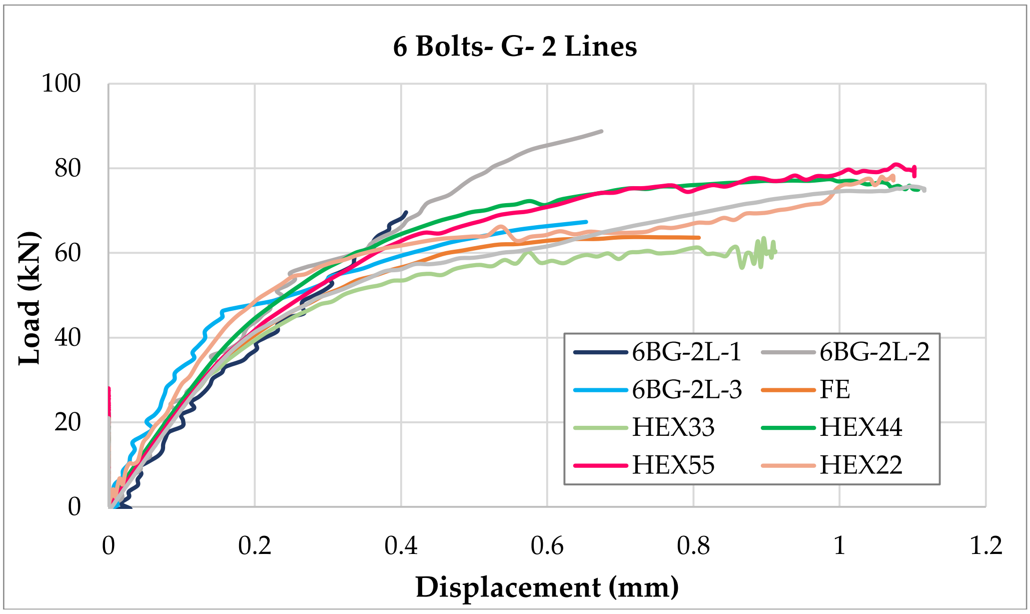


Figure (11): Load-displacement curves of the six glued-and-bolted steel-plate connections modeled using five different mesh sizes

CONCLUSIONS

This study incorporated three distinct types of connection; namely, bolted connection, adhesive connection and bolted connection with adhesive. The primary findings of this study can be succinctly outlined as follows:

- The experimental observations revealed that the addition of up to four bolts together with glue in the connection did not enhance the overall bond capacity. In fact, it was found that the utilization of glue alone was adequate to achieve a bond capacity of up to 40 kN. Alternatively, the utilization of six bolts alone was able to yield this value. Thus, it was established that both methods can be recommended when targeting a value of up to 40 kN.
- The results revealed that a system comprised of at least six bolts and glue together could be used to enhance the capacity of the connection. In cases where it is impractical to add more bolts or because of the limitations of the distance between bolts, glue can be applied instead. It is recommended that a system comprised of glue with six bolts distributed equally along two lines be utilized to attain an ultimate capacity ranging from 40 kN to 70 kN. However, it is recommended that glue with eight bolts distributed over two lines be used to attain an ultimate capacity ranging between 70 kN and 90 kN.
- The finite-element models developed in the ABAQUS software resulted in outcomes that were in good agreement with the results obtained in the experimental testing. Therefore, these models can be considered as calibrated models and be further used for future parametric investigation to account for a variety of cases, such as the examination of various plate thicknesses/dimensions and sensitivity analyses for bolt arrangements.

Acknowledgements

The authors would like to thank the Deanship of Scientific Research at Al al-Bayt University, Al-Mafraq, Jordan, for funding this research under Grant No. 9938/2021.

REFERENCES

Abdel-Jaber, M., Abdel-Jaber, M.S., Beale, R.G., Allouzi, R., and Shatarat, N.K. (2020). "Properties of tube and fitting scaffold connections under cyclical loads". Journal of Constructional Steel Research, 168, 106008.

Abendeh, R.M., Salman, D., and Al-Louzi, R. (2022). "Experimental and numerical investigations of interfacial bond in self-compacting concrete-filled steel tubes made with waste steel slag aggregates". Developments in the Built Environment, 11, 100080.

Al-Chaar, G.L., and Mehrabi, A. (2008). "Constitutive models for non-linear finite-element analysis of masonry prisms and infill walls". Engineer Research and Development Center Champaign II. Construction Engineering Research Lab.

Ali, M.M., Oehlers, D.J., and Bradford, M.A. (2005). "Debonding of steel plates adhesively bonded to the compression faces of RC beams". Construction and Building Materials, 19(6), 413-422.

Allouzi, R., and Irfanoglu, A. (2018). "Finite-element modeling of reinforced-concrete frames with masonry infill walls subjected to lateral-load reversals". The Masonry Society Journal, 36 (1), 33-46.

Allouzi, R.A., Almasaeid, H.H., Salman, D.G., Abendeh, R.M., and Rabayah, H.S. (2022). "Prediction of bond-slip behavior of circular/squared concrete-filled steel tubes". Buildings, 12 (4), 456.

Bedon, C., Machalická, K., Eliášová, M., and Vokáč, M. (May 2018). "Numerical modeling of adhesive connections including cohesive damage". In: Challenging Glass Conference Proceedings, 6, 309-320.

Berthet, J.F., Yurtdas, I., Delmas, Y., and Li, A. (2011). "Evaluation of the adhesion resistance between steel and concrete by push-out test". International Journal of Adhesion and Adhesives, 31 (2), 75-83.

Chesoan, A., Stratan, A., Neagu, C., and Dubina, D. (2020). "Experimental investigation of the length influence on removable links". Proceedings IRF2020: 7th ICIRF.

Ciupack, Y., Pasternak, H., Mette, C., Stammen, E., and Dilger, K. (2017). "Adhesive bonding in steel construction: Challenge and innovation". Procedia-Engineering, 172, 186-193.

Correia, J.A.F.O., De Jesus, A.M., Silva, A.L., Pedrosa, B., Rebelo, C., and Calçada, R. (2017). "FE simulation of SN curves for a riveted connection using two-stage fatigue models". Advances in Computational Design, an International Journal, 2, 333-348.

da Silva, L.F.M. (2005). "Design of adhesively-bonded composite joint: Fatigue and fracture of adhesively-bonded composite joints: Behavior, simulation and Modeling". Edited by Vassilopoulos, A.P., Woodhead Publishing.

da Silva, L.F.M., and Campilho, R.D.S.G. (2015). "Design of adhesively-bonded composite joints". In: Fatigue and Fracture of Adhesively-bonded Composite Joints, 43-71. Woodhead Publishing.

Dassault Systèmes Simulia Corp. (2014). "ABAQUS analysis user's manual online documentation". 2014, Version 6.14. Providence, RI, USA.

Di Scalea, F.L., Bonomo, M., and Tuzzeo, D. (2001). "Ultrasonic-guided wave inspection of bonded lap joints: Noncontact method and photoelastic visualization". Research in Nondestructive Evaluation, 13 (3), 153-171.

Giurgiutiu, V., Lyons, J., Petrou, M., Laub, D., and Whitley, S. (2001). "Fracture mechanics testing of the bond between composite overlays and a concrete substrate". Journal of Adhesion Science and Technology, 15 (11), 1351-1371.

Helincks, P., De Corte, W., Klusák, J., Boel, V., and de Schutter, G. (2013). "Experimental investigation of the influence of the bond conditions on the shear bond strength between steel and self-compacting concrete using push-out tests". Key Engineering Materials, 525, 205-208.

Iannone, F., Latour, M., Piluso, V., and Rizzano, G. (2011). "Experimental analysis of bolted steel beam-to-column connections: Component identification". Journal of Earthquake Engineering, 15 (2), 214-244.

Kumar, P., Patnaik, A., and Chaudhary, S. (2017). "A review on application of structural adhesives in concrete and steel–concrete composite and factors influencing the performance of composite connections". International Journal of Adhesion and Adhesives, 77, 1-14.

Latour, M., and Rizzano, G. (2012). "Experimental behavior and mechanical modeling of dissipative T-stub connections". Journal of Structural Engineering, 138 (2), 170-182.

Latour, M., Piluso, V., and Rizzano, G. (2018). “Experimental analysis of beam-to-column joints equipped with sprayed aluminium friction dampers”. Journal of Constructional Steel Research, 146, 33-48.

Machalická, K., Eliášová, M., and Vokáć, M. (2016). “Experimental and numerical analysis of acrylate adhesive joints”. In: Proceedings of ESAT2016-2nd International Conference on Engineering Sciences and Technologies.

Marcon, M., Vorel, J., Ninčević, K., and Wan-Wendner, R. (2017). “Modeling adhesive anchors in a discrete-element framework”. Materials, 10 (8), 917.

Meaud, C., Jurkiewiez, B., and Ferrier, E. (2014). “Steel-concrete bonding connection: An experimental study and non-linear finite-element analysis”. International Journal of Adhesion and Adhesives, 54, 131-142.

Montgomery, J. (May 2008). “Boundary condition influences on shank stress in 3D solid-bolt simulation”. In: Conference Proceedings, 19-22.

Nastri, E., and Plaitano, F. (April 2022). “A review on the removable link in eccentrically braced frames: Benefits and performances”. In: AIP Conference Proceedings, 2425 (1), 120008. AIP Publishing, LLC.

Pandulu, G., Jayaseelan, R., and Jeganathan, S. (2020). “Performance of RCC beams laminated with kevlar fabric”. Jordan Journal of Civil Engineering, 14 (2).

Petrie, E.M. (2007). “Handbook of adhesives and sealants”. McGraw-Hill Education, New York.

Piekarczyk, M., and Grec, R. (2012). “Application of adhesive bonding in steel and aluminium structures”. Archives of Civil Engineering, 58 (3), 309-329.

Plaitano, F. (2020). “Experimental tests and FEM simulations of bolted links with flush and extended end-plate connections under monotonic and cyclic loads”. Master Thesis, University of Salerno, Fisciano, Italy, 15 June 2020.

Plaitano, F., Stratan, A., and Nastri, E. (2022). “Simplified modeling of failure in high-strength bolts under combined tension and bending”. Journal of Composites Science, 6 (10), 302.

Pravdová, I., Machalická, K., and Eliášová, M. (2016). “Steel-glass structural elements with a new generation of adhesives”. Proceedings of Challenging Glass, 5.

Rodrigues, M.F., Correia, J., Pedrosa, B., De Jesus, A., Carvalho, B., Rebelo, C., Xavier, J., and Calçada, R. (2017). “Numerical analysis of a double-shear standard bolted connection considering monotonic loadings”. Engineering Structures and Technologies, 9 (4), 183-194.

Rokhlin, S.I. (1991). “Lamb wave interaction with lap-shear adhesive joints: Theory and experiment”. The Journal of the Acoustical Society of America, 89 (6), 2758-2765.

Silva, J.D. (2009). “Comparação entre o comportamento à fadiga de ligações rebitadas e aparafusadas”. Universidade de Trás-os-Montes e Alto Douro, Vila Real.

Tartaglia, R., and D’Aniello, M. (June 2021). “Behaviour of T-stub under modes 2 and 3 with HV and HR bolts”. In: Proceedings of the 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Athens, Greece, 28-30.

Verbruggen, S., De Sutter, S., Iliopoulos, S., Aggelis, D.G., and Tysmans, T. (2016). “Experimental structural analysis of hybrid composite-concrete beams by digital image correlation (DIC) and acoustic emission (AE)”. Journal of Non-destructive Evaluation, 35, 1-10.

Yonathan Sunarsa, T., Aryan, P., Jeon, I., Park, B., Liu, P. and Sohn, H. (2017). “A reference-free and non-contact method for detecting and imaging damage in adhesive-bonded structures using air-coupled ultrasonic transducers”. Materials, 10 (12), 1402.

Zhan, Y., Ma, Z.J., Zhao, R., Li, G., and T. (2016). “Interface behavior between steel and concrete connected by bonding”. Journal of Bridge Engineering, 21 (6), 04016026.