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Numerical investigation of modified splice plate beam-to-beam connections for prefabricated composite structure

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Abstract: *Prefabricated construction has been rising dramatically in the construction industry in recent times. On the other hand, it is equally complicated and laborious to design and install the prefabricated structures on site. The reason behind this can be credited to the limited design guidelines available and the massive structural parts. This research has been carried out to overcome shortcomings of the prefabricated composite construction. In this paper, the idea of discontinuous beams and a beam-to-beam connection system has been proposed for the prefabricated construction. Modified splice plate bolted connection has been suggested for the discontinuous beams. The proposed connection is similar to splice plate bolted connection, but welding between splice plate and beam web is introduced. This paper mainly investigated the behaviour of modified splice plate bolted connections using finite element (FE) analysis and compared its results with continuous beam. Based on FE modelling results, it has been found that the proposed connection system having welding provides higher strength to the discontinuous beam compared to the same discontinuous beams connected by conventional splice plate bolted connection systems. Splice plates welded to the web of the steel beam need to be fabricated in a factory and normal bolts are installed on the site of the building construction. Thus, it can be concluded from this research that the massive continuous beams can be replaced by discontinuous beams through a presented connection system for prefabricated construction.*

***Keywords**: Prefabricated constructions; Discontinuous beam; Beam-to-beam connection; Splice plate bolted connection system; Finite element modelling.*

1. Introduction

Steel construction has the emerging market in the construction industries. In conjunction with this, prefabricated concrete structures have been rapidly replacing the in-situ construction in these growing construction industries (Shechter et al., 1984). The numerous benefits such as improved construction quality, reduced construction cost, less construction time, lower site disruption, better site safety, easy repair and maintenance, higher sustainability, recyclable waste etc. can be credited for the rapid growth of this construction technology (Hassan et al, 2018). This construction procedure has its extensive use all over the world: accounting for more than 80 % in Sweden, around 20 % in New Zealand and Japan and the figure is around only 10 % in Australia (Heaton et al., 2017; Hassan et al., 2018). It has been foreseen that this practice would have been double in the coming 5 years in Australia (Heaton, 2017).

Steel beams have been universally used in the construction of composite structures due to its high constructional and structural amelioration (Wu et al., 2007; Katwal et al., 2018). Reporting its benefits, different literature has suggested for the combined application of steel beams connected to floor slabs using the shear connectors/ bolts rather than steel beams and reinforced concrete slabs without composite actions (Hick & Lawson, 2003). Nonetheless, the practice of using composite beam with RC slab is very limited in prefabrication construction.

Despite its rising popularity, limited guidance on a detailed design is available for their application in steel framed structures. Consequently, prefabrication has been specialised in the structural system as a single material steel, timber or reinforced concrete rather than composite prefabricated structure (Lam et al., 2000). This has provided a good platform for a number of researchers. A number of researches have been carried out for the prefabricated composite structures. However, all the research and outcomes are implied for the design of the continuous beam (Uy et al., 2017; Lam et al., 2002; Lam et al., 2017). This project has been undertaken with a purpose to investigate the response of the discontinuous beam interconnected with each other under normal loading conditions.

Traditional continuous beams can be designed to a targeted strength. Despite this, it is laborious to carry long and heavy beams up to the site and install for prefabrication construction. This drawback can be conquered by the concept of discontinuous beams as it increases the portability and flexibility in connection. However, it is very challenging to design the connection of discontinuous beams and to obtain the same strength as a continuous beam. The current research will address this challenge with a proper connection design. For the conventional construction of steel structures, splice plate connections have been used to connect the steel beam to steel beam. In this type of connection, two or more splice plates and a number of bolts are used to the beams each other. In this paper, modified splice plate (MSP) connections are proposed for the prefabricated construction of steel beam-to-steel beam connections. In this paper, the feasibility study of proposed connections for discontinuous beams without slab will be studied using finite element (FE) analysis to understand the structural behaviour of the proposed connections.

2. Methodology

2.1 Proposed Beam-to-Beam Connections

In this research, the hypothesis made is that the ultimate strength of the discontinuous beam being used in prefabricated construction will be as close to the ultimate strength of the continuous beam under the same loading condition and beam-to-beam connections will be designed based on this strength assumption. It is targeted to get the discrepancy of ± 10 %. For beam-to-beam connection, the point of contra-flexure is to be selected as at this point of the bending moment becomes zero and hence to some extent becomes easier to overcome the flexural failure of beam. Another hypothesis is that the connection system can overcome the shear failure easily of bolts. For prefabricated construction of steel-concrete composite structures, modified

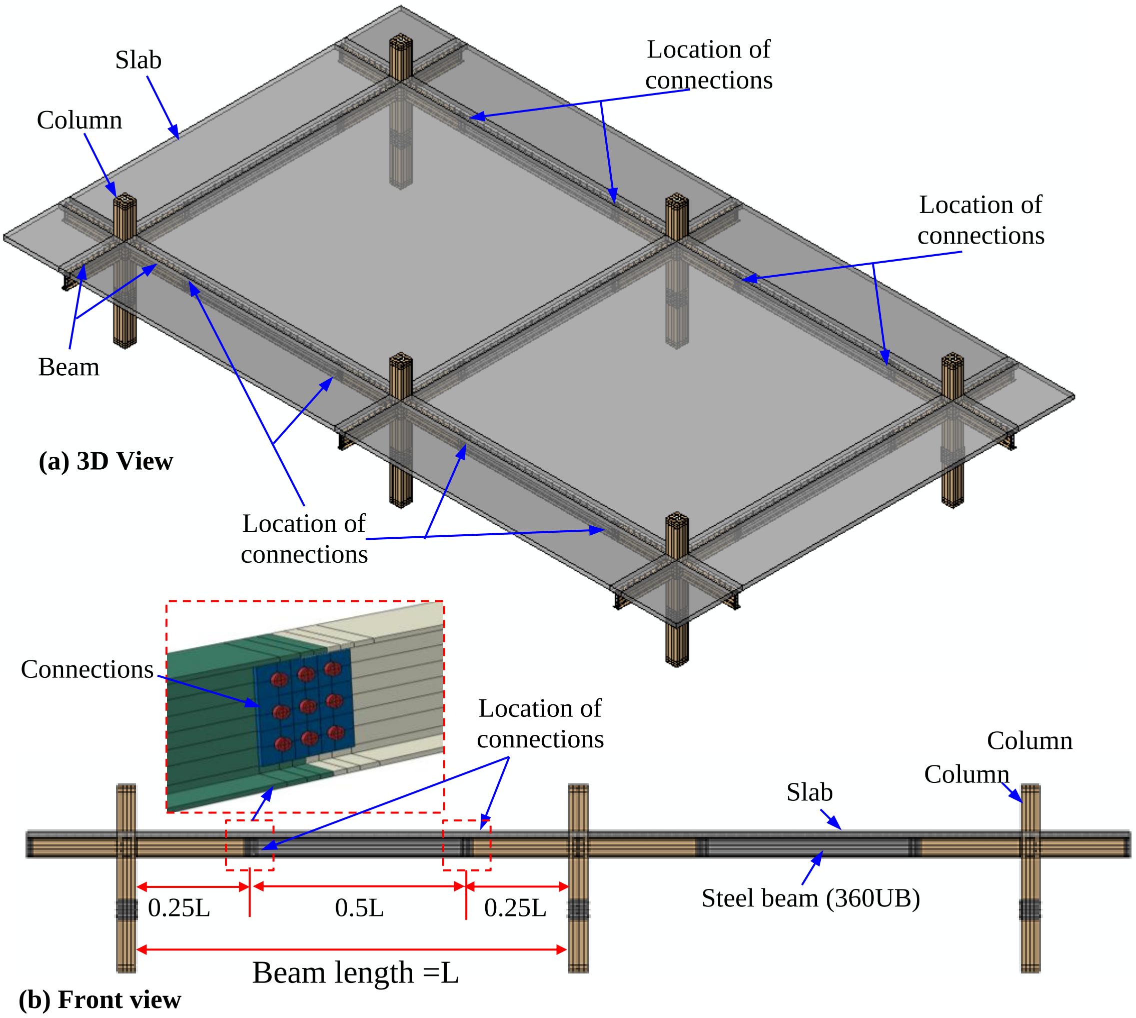


Figure 1. Location of beam-to-beam connections for prefabricated composite structures

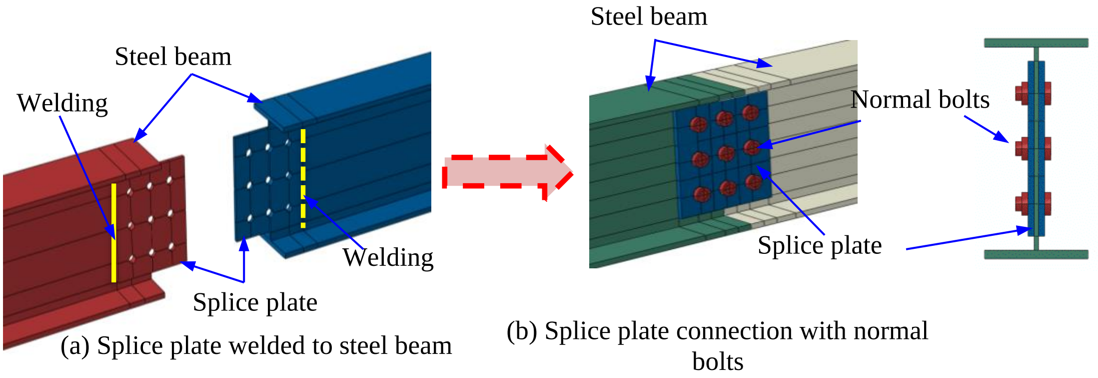


Figure 2. Details of proposed beam-to-beam connections with splice plates and normal bolts

splice plate connections are proposed where splice plates welded to the steel beam will be fabricated in the factory and then bolts will be used to connect the two discontinuous steel beams on the construction site only. In this method, the strength capacity of the proposed connections can be enhanced as well as the installation cost to handling the splice plates at the construction site can be minimised, due to the welding between the steel beam and splice plate. Figure 1 shows the location of the proposed connections that can be used for the prefabricated constructions. Figure 2 (a) shows the two connection component plates are attached to each part of the beam through welded connection. These two separate parts are assembled and connected by the bolt to make a beam-to-beam connection as shown in Figure 2(b).

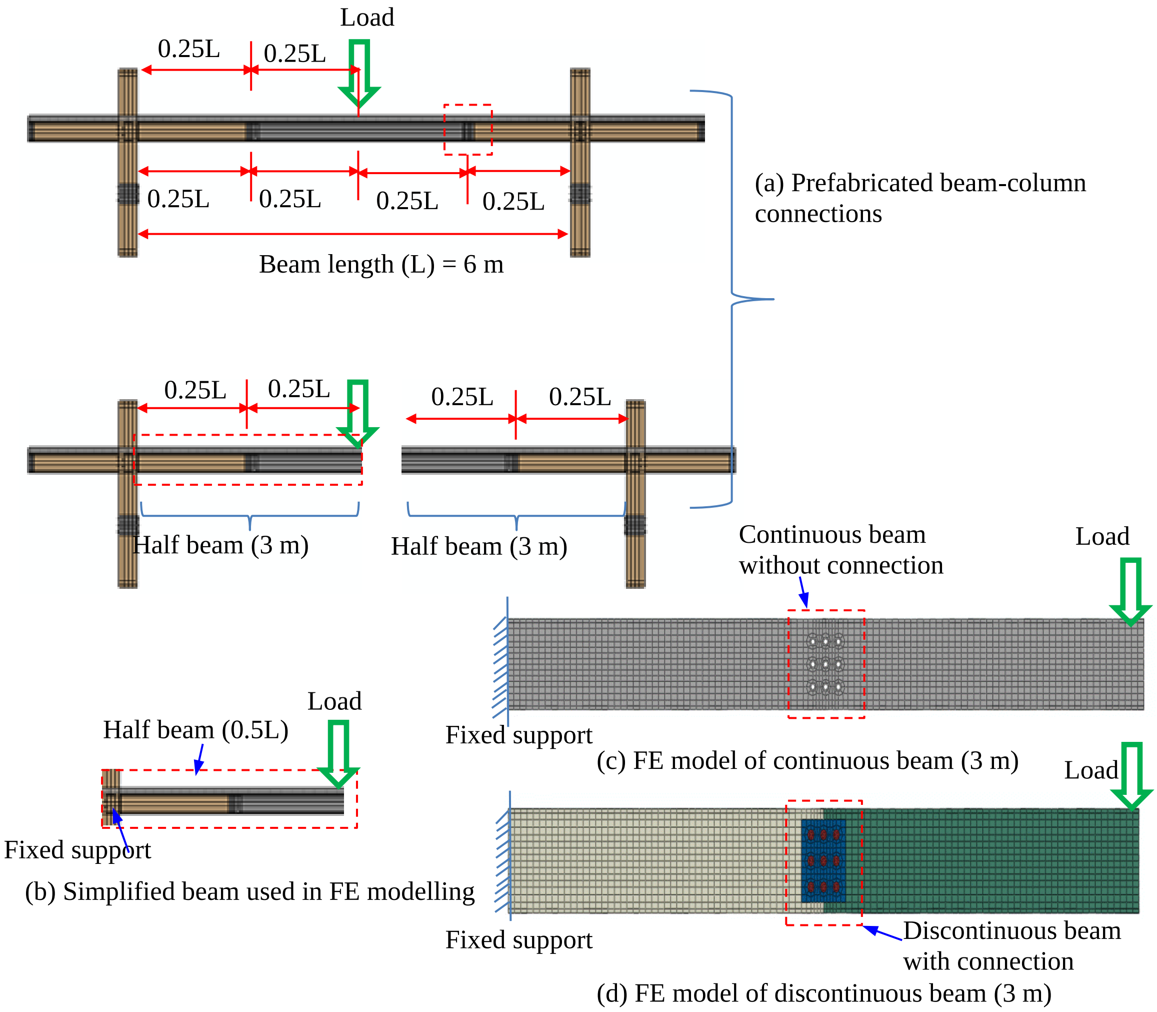


Figure 3. Details of half beam used in FE modelling

2.2 FE modelling of proposed connections

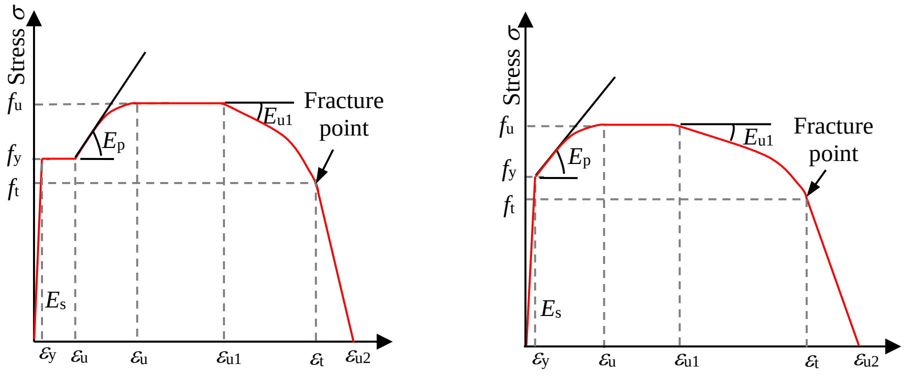
Finite element (FE) model has been established using general FE analysis software ABAQUS. The steel beams (310 UB 46.2), splice plates (210×244× 8 mm) and bolts (8.8 grade M20) are simulated using C3D8I elements [Hassan et al., 2014]. The minimum and maximum sizes used in the meshing of all components are 10 mm to 30 mm. Tie constraints are used for welding between the splice plate and steel beam web; remaining contacts are defined using hard surface-to-surface contacts. The friction coefficient used for hard contact is 0.25 for steel to steel contact [Hassan et al., 2014; Hassan et al., 2016]. For the simplicity of analysis, half of the beam is considered in FE modelling as shown in Figure.3 (b).

2.3 Material Models

The full-range stress-strain material models are used to simulate the strain hardening and softening behaviour of steel beam as shown in Figure. 4(a) and structural bolts as shown in Figure. 4(b). These two models were developed by Hassan [2016] based on Tao model (2013). The details of these two models are given in Hassan [2016]. The yield strength, ultimate strength and elastic modulus used in the FE modelling of the steel beam, splice plate and bolt are given in Table 1.

Table 1 Material properties of structural steels and structural bolts

Materials Properties	Beam flange	Beam flange	Splice plate	Bolt
Yield stress (MPa)	352	370	388	640
Ultimate stress (MPa)	535	534	506	800
Elastic modulus(GPa)	198	203	206	200



(a) Steel beam (b) Shear stud

Figure 4. Full-range stress-strain curves for steel beams and shear studs (Hassan, 2016)

2.4 Load and Boundary Conditions

The load is applied at the end of the steel beam. As the steel beams are connected to columns using either welding or bolting, one end of the steel beam is considered as rigid connections. Based on this assumption, one end of the steel beam is restrained against UX, UY, UZ, RX and RZ as shown in Figure 3(c) for continuous beam and in Figure 3(d) for discontinuous beam. Nonlinear FE analysis has been conducted by considering the material nonlinearity i.e. nonlinear stress-strain curves, geometric non-linearity and boundary nonlinearity. Geometric and boundary nonlinearities are assigned using NLGEOM and CONTACT PAIR comments respectively in ABAQUS. The load is applied under displacement control method using a dynamic implicit method.

2.5 Verification

To verify the FE model, the test specimen is modelled using ABAQUS. Wang et al. (2009) conducted tests on blind-bolted endplate connections to CFST column (CJM1). The comparative results of the FE model and test of the specimen CJM1 subjected to bending are shown in Figure 6. The predicted load–displacement curves obtained from the FE models of these specimens agree very closely with the test results.

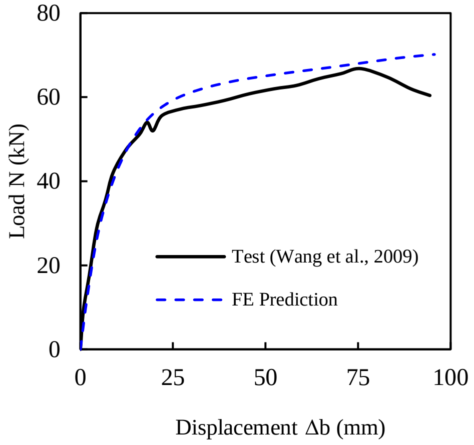


Figure 6. Comparison of FE model result with test result of cantilever beam i.e. blind-bolted endplate connections in bending load

3. Results and discussion

3.1 Comparison between continuous and discontinuous beams

The continuous beam and splice plate bolted (SPB) discontinuous beam has been modelled using finite element software ABAQUS to understand the behaviour differences in term of ultimate capacity and stiffness. In both cases, the same universal steel beam (360 UB 46.2) has been used. As mentioned in the previous section, the SPB discontinuous beam introduced in this paper is mainly fabricated from two segments of beams by connecting the splice plates (210×244× 10 mm) and normal structural bolts (M20). The results obtained from the analysis of the continuous beam and discontinuous beam with different connection systems has been discussed in below.

Figure 7 shows how the load-deformation curves of continuous and SPB1 discontinuous beams. It can clearly be seen that the ultimate capacity of the discontinuous beam is significantly reduced compared to the continuous beam, which is well expected because of the discontinuity. It is also noticed that the deflection of discontinuous beams at the connection point is higher than the continuous beam. In Figure 7, SPB1 is a discontinuous beam without pretension force. From the FE modelling results, it is observed that the continuous beam can resist a very high load of up to 88.81 KN. However, for the discontinuous beam at the same deformation, the ultimate failure occurs even at a very small load of 45.32 KN. When pretension force is applied to the bolt, the ultimate capacity (56.53 KN) of SPB2 discontinuous beam, as shown in Figure 8, is increased compared to the SPB1 discontinuous beam without pretension force. It was also noticed that the initial stiffness of both the discontinuous beams (SPB1 & SPB2) is significantly lower compared to the continuous beam.

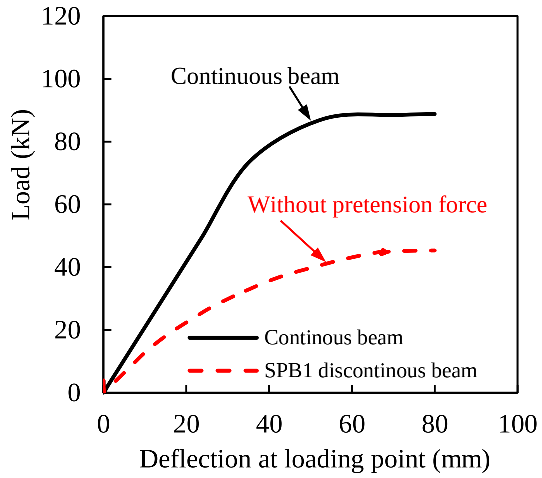


Figure 7. Load vs displacement curves of continuous and SPB1 discontinuous beam

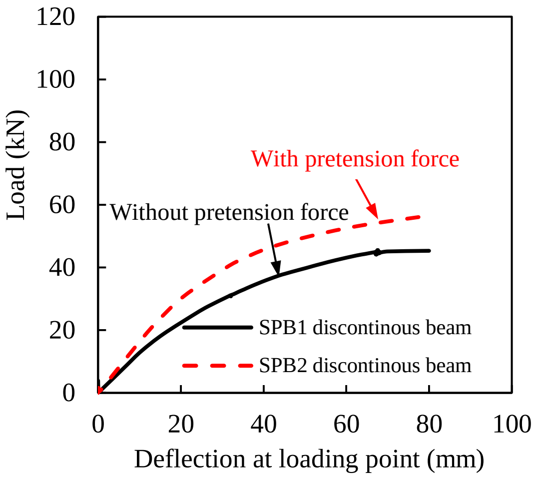
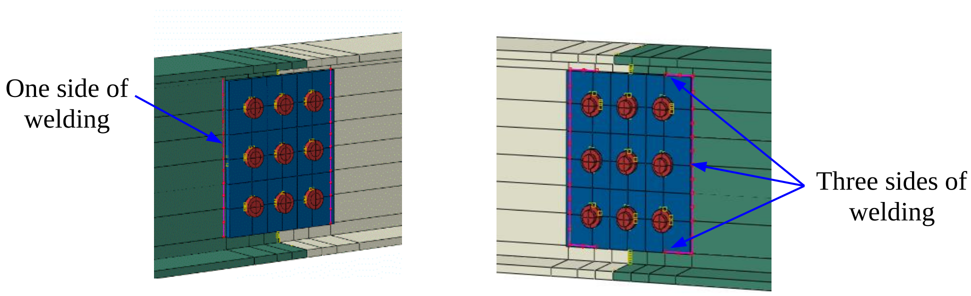


Figure 8. Effect of bolt pretension force on the discontinuous beam

3.2 Effect of welding between splice plate and beam web

The conventional splice plate bolted (SPB) discontinuous beam has been modified by introducing welding between splice and beam web, which is referred to here as a modified splice plate bolted (MSPB) discontinuous beam. The dimension used in MSPB discontinuous beams (MSPB1 & MSPB2) is similar to the conventional SPB discontinuous beam (SPB2). The main difference between the MSPB1 & MSPB2 is the welding area. For MSPB1 discontinuous beam, welding is made between one side of the splice plate and web of a beam whereas for the MSPB2 discontinuous beam, welding is made between three sides of the splice plate and web of a beam. The welding locations of these two MSPB discontinuous beams are shown in Figure 9. In can be seen that in the MSPB1 discontinuous beam, the plates and the beam web are connected by the vertical welding connection and for the MSPB2 discontinuous beam, the welded connection was upgraded to bidirectional welding between the plate and web of beam.

Figure 10 shows the FE modelling results of the modified SPB discontinuous beams (MSPB1 & MSPB2). The FE modelling results of the MSPB1 and MSPB2 discontinuous beams are also compared with the continuous beam and the conventional SPB discontinuous beam. The FE results show that the strength of MSPB1 discontinuous beam (84.38 kN) is increased significantly compared to the convention SPB2 discontinuous beam (56.53 kN). This 49.65% strength increase is due to the welding between one side of the splice plate and beam web. When three sides of welding are used in the MSPB2 discontinuous beam, the maximum ultimate load at same deformation is 86.29 kN, which is 2.2% higher compared to the one side welding used in the MSPB1 discontinuous beam. When FE modelling results of the modified SPB discontinuous beams are compared with continuous beams, their strength is found to be very close to the continuous beam (88.81 kN). The strength difference between the modified SPB discontinuous beams and the continuous beam is found to be 2.9-5.25 %, which is below 10%.



(a) MSPB1 connection with 1side welding (b) MSPB2 connection with 3sides welding

Figure 9. Welding locations of MSPB1 and MSPB2 discontinuous beams

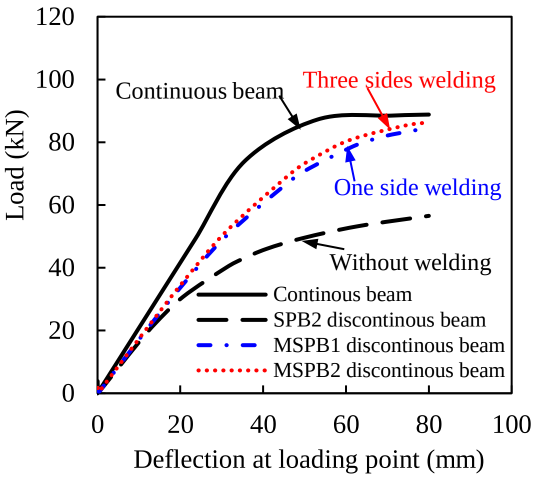
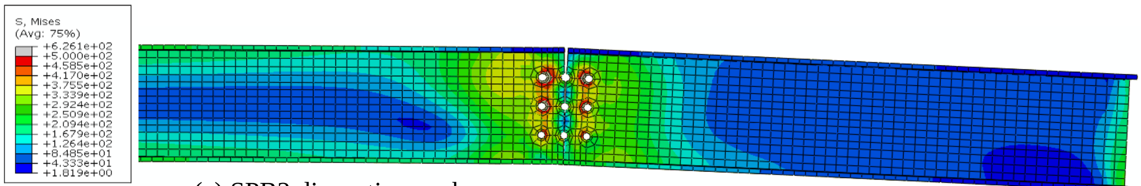


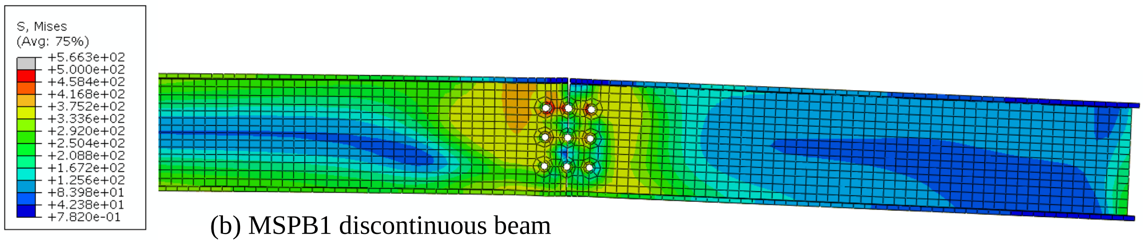
Figure 10. Load vs displacement curves of conventional and modified SPB discontinuous beams

3.3 Stress generated on beams due to conventional and modified SPB connections

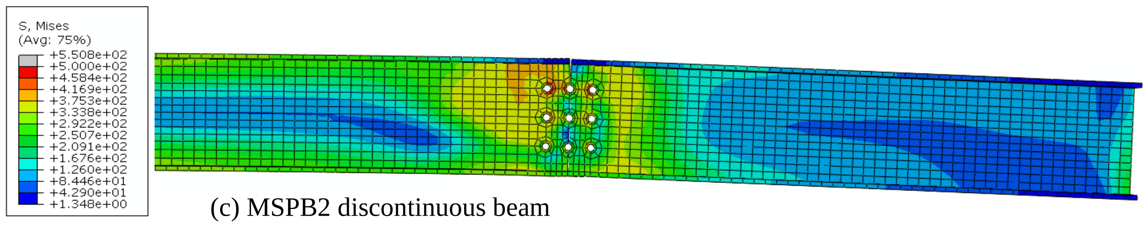
Stress analysis has been performed using FE analysis to determine the stress distribution on the discontinuous steel beams due to different conditions of SPB connections. The FE results of stress analysis as shown in Figure 11 are presented in term of Von Mises stress to identify the failure condition. The Von Mises stress failure criterion has been used to identify the material failure condition. In the Von Mises stress failure criterion, when the Von Mises stress at a particular location exceeds the yield material strength, then the material yields at that location. If the Von Mises stress at a particular location exceeds the ultimate material strength, the material ruptures at that location. From the Von Mises failure criterion and the stress contour plot as shown in Figure 11(a), it is observed that the steel beam failure is more remarked near all bolt holes of the SPB2 discontinuous beams connected by conventional SPB connection. However, when a modified SPB connection is used to connect two beams, the stress concentration on the MSPB1 and MSPB2 discontinuous beams is less significant as shown in Figure 11(b) and Figure 11(c), respectively, compared to the SPB2 discontinuous beam.



(a) SPB2 discontinuous beam



(b) MSPB1 discontinuous beam

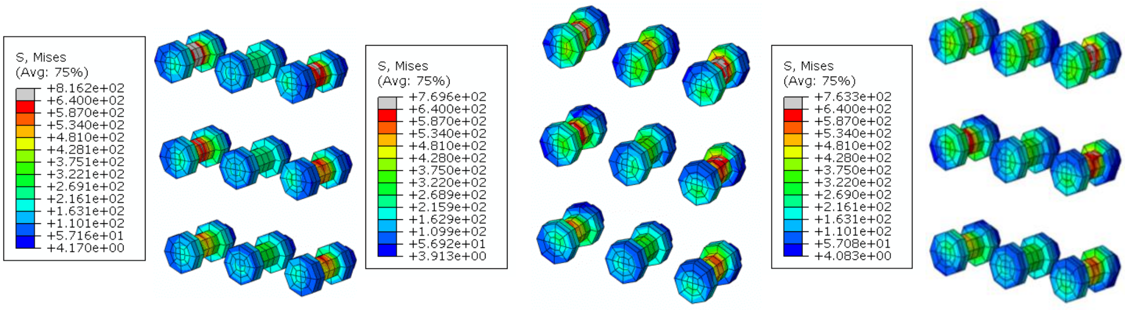


(c) MSPB2 discontinuous beam

Figure 11. Stress generated on beam due to the conventional and modified SPB connections

3.4 Stress generated on bolts due to conventional and modified SPB connections

Figure 12 shows the stress distribution on the bolts due to the different types of SPB connections. When conventional bolts are used to connect the two beams of SPB2 discontinuous beams, the stress concentration on the bolts exceeded the ultimate strength of bolts (fu =800MPa). This indicates that the SPB2 discontinuous beam failed due to the rupture of the bolts. However, when proposed modified SPB connections are used in the MSPB1 and MSPB2 discontinuous beams, the stress concentration is lower than the ultimate strength of bolts. This indicates that the MSPB1 and MSPB2 discontinuous beams failed due to the yield of the bolt material not rupturing.

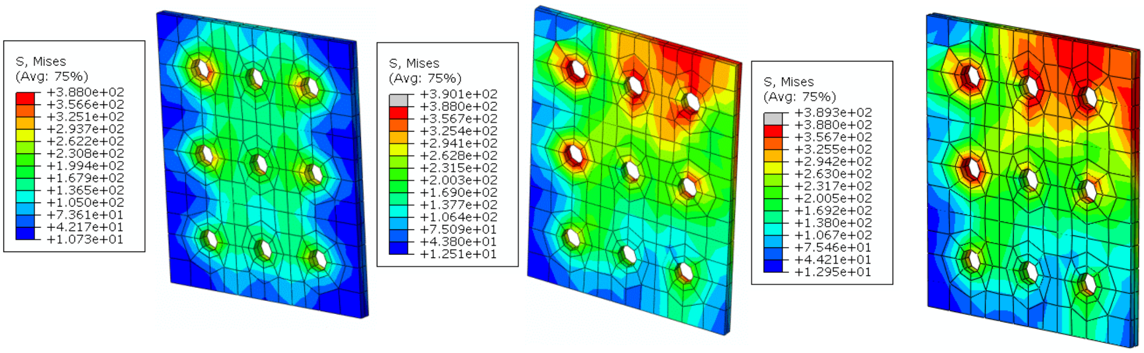


(a) SPB2 discontinuous beam (b) MSPB1 discontinuous beam (c) MSPB2 discontinuous beam

Figure 12. Stress generated on bolts due to the conventional and modified SPB connections

3.5 Stress generated on splice plate due to conventional and modified SPB connections

The stress distribution on the splice plate due to the different types of SPB connections is shown in Figure 13. The stress generated on the splice plate due to the conventional SPB connection as shown in Figure 13(a) is lower than the yield strength of the splice plate (fy = 388 MPa). However, for the modified SPB connection, the stress observed on splice plate as shown in Figure 13(b) for MSPB1 discontinuous beams and Figure 13(c) for MSPB2 discontinuous beams is higher than its yield strength (fy = 506 MPa), but lower than the ultimate strength. This also indicates that MSPB1 and MSPB2 discontinuous beams failed due to combined yielding of the splice plate and bolts. But for the SPB2 discontinuous beams, the failure is due to the failure of bolts. When structure fails due to the bolts, it would be a catastrophic failure, which is not expected. It can be concluded from the stress analysis of the beam, bolts and plate that when one side welding is considered in the conventional SPB connections to connect two beams of the discontinuous beams, the failure can be control by the combined failure of beam, bolt and splice plate. Such a design can be economical for the prefabricated construction as the same configuration of connections can resist more loads which will be closed to the continuous beam.



(a) SPB2 discontinuous beam (b) MSPB1 discontinuous beam (c) MSPB2 discontinuous beam

Figure 13. Stress generated on splice plate due to the conventional and modified SPB connections

4 CONCLUSION

A modified splice plate bolted connection has been proposed to connect steel beams to steel beams for the prefabricated construction. This paper mainly investigated the behaviour of modified splice plate bolted connections using finite element (FE) analysis. The following conclusion can be drawn based on the FE modelling results reported in this paper:

(1) When two beams are connected using conventional splice plate bolted connections, the ultimate capacity of discontinuous beams is reduced significantly compared to the continuous beam.

(2) When welding between the splice plate and beam web is considered in the conventional splice plate bolted connections to connect two beams, the ultimate capacity of the discontinuous beams is enhanced significantly

compared to the discontinuous beams having conventional splice plate bolted connections, but lower than the continuous beam.

(3) When one side or three sides welding is considered in modified splice plate bolted connections, the strength difference between continuous and discontinuous beams is below 10%.

(4) When modified splice plate bolted connections are used, the failure of discontinuous beams can be controlled by the combined failure of beam, bolt and splice plate. Hence it can be said that a discontinuous beam can be used instead of a continuous beam by proper design of modified splice plate bolted connections.

Further experimental research needs to be conducted to verify the proposed modified splice plate bolted connections. The number and locations of bolts and splice plate thickness can also be optimised in future study.

5. ACKNOWLEDGEMENTS

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