Modified Connection Details for Single Plate Steel Connections under Fire

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Abstract:

Single plate (shear tab) connections connect a beam to a girder or to a column, and they are designed to resist only shear loads. In a fire event, the axial restraint provided by adjacent structure creates unanticipated compressive and tensile forces in the beam and thus the connection. Using finite element (FE) models with contact elements, this study examines shear tab connections under fire. The model, validated by experimental data, represents the connection as well as a portion of the surrounding structure in a composite floor framing system. By extending the model beyond the connection region, the combination of shear, axial force and moment are properly represented in the connection during the fire. Previous studies have shown that large beam rotations and tensile forces result in bolt tear out (beam bearing) or bolt shear failure. This study shows how some simple modifications in the connection model affects the response (if at all).

1. Introduction:

In a fire event, the axial restraint provided by adjacent structure creates compressive and tensile forces in the beam and thus the connection. Real fire events have shown that tensile forces, which can develop during the heating phase (with beam catenary action) and the cooling phase of the fire (with beam contraction), have led to failure of simple shear connections in some cases. These simple shear connections are designed only to resist shear loads but not the axial loads imposed by the fire. There are several types of simple shear connections and this paper focuses on a single plate (shear tab) connection type which is commonly used in United States.

After recent fire events and full-scale experiments [Wald et al. 2006; Bailey et al. 1999], it became obvious that load and rotation capacity of connections mostly govern the behavior of floor systems in a building under fire. This experimental fact has been investigated and confirmed by numerical methods using commercially available finite element software ABAQUS [Garlock and Selamet 2009; Selamet and Garlock 2008]. In such investigations single plate connections are found to be most vulnerable to large tensile forces developed in connected members during the cooling phase of a natural fire.

Since the tensile capacity of such connection directly relates to the collapse or survival of floor systems, it is important to conduct a parametric study by changing the connection geometry and material details and to evaluate such changes on the connection performance. This paper examines a change in bolt hole size (geometry) and a change in bolt grade (material). The material presented here is only the beginning of a larger study of shear connections under fire.

2. Overview of FE Model:

A finite element model is formed from a portion of a floor system from Cardington experiment as shown in Figure 1 [Wald et al. 2006]. Figure 2 shows the floor subassembly and connection finite element model as well as the fire time-history imposed on the model based on the Cardington experiment. The FE model details are given by the authors in other papers [Garlock and Selamet 2009; Selamet and Garlock 2008] and here we provide only a brief account. An uncoupled thermo-mechanical analysis is used on the subassembly where in the first phase (the thermal analysis) the heat transfer method provides transient nodal temperatures with respect to time. In the second phase (the mechanical analysis), the nodal temperatures are read from the thermal analysis and corresponding temperature dependent mechanical material (Eurocode) properties are used.

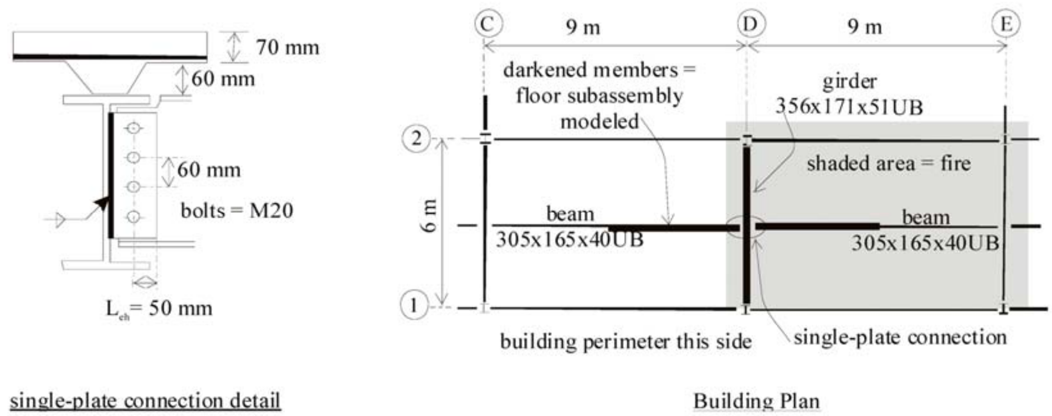
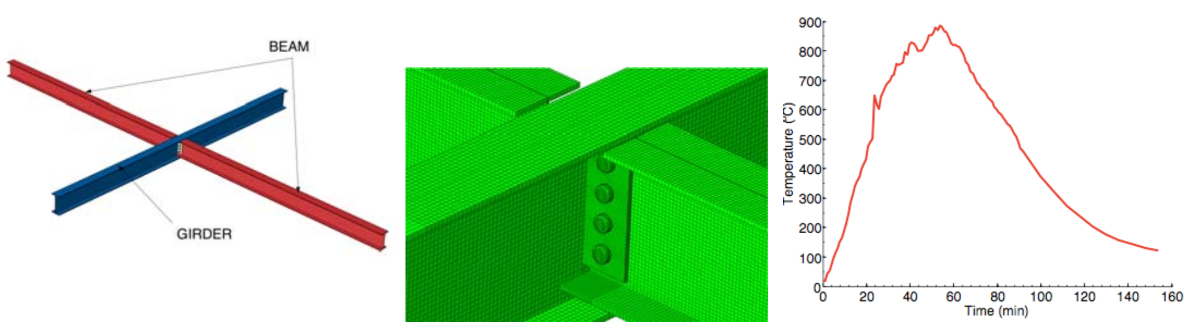


FIGURE 1 - STRUCTURAL DESIGN OF THE 2003 CARDINGTON TESTS [WALD ET AL. 2006].



(A) SUBASSEMBLY (B) CONNECTION DETAIL (C) IMPOSED FIRE

FIGURE 2 - FINITE ELEMENT MODEL OF FLOOR SUBASSEMBLY AND IMPOSED FIRE.

The boundary conditions of the subassembly are applied to represent realistic surrounding constraints like in the Cardington experiment. The flexible axial restraint provided to the girder by the perimeter column D1 is represented by springs with a stiffness based on Quiel and Garlock [2008]. Symmetry boundary conditions are imposed on the beam ends (i.e., fixed horizontal translation at every node). Further, the girder ends are modeled as partially pinned using connector elements and coupling constraints in ABAQUS. The top flange of the beams is fixed in the lateral direction to represent the restraint provided by the slab and avoid lateral torsional buckling. The strength of the connection weld (Figure 1) is not represented in the model; therefore it is assumed that this weld will not fail. Cardington experiment shows that the connection region stays relatively colder than the beam midspan. To create this heat sink effect, the fire load on connection components is scaled down so that the finite element model's thermal response matches closely to the results measured in the test.

Material properties of different components of the subassembly are taken directly from Cardington experiment measurements [Bailey at al. 1999] at ambient temperatures. Eurocode reduction factors were used to reduce the stress-strain material properties at elevated temperatures of the connection members except the bolts. For the bolts, Kirby's suggested reduction factors were used [Kirby 1995].

3. Modifications in Single Plate Connection:

This paper describes the beginning of a project that will examine if cost-effective modifications to shear tab connection details can result in improved fire performance. The section describes only two modifications: size of web bolt holes and change of bolt grade. The authors are currently continuing this study to include other modifications.

3.1 Oversize bolt-holes in the coped beam web:

The effect of oversize bolt-holes in both beam web and connection plate is investigated. The aim is to relieve contact forces acting on the bolt region by allowing some free movement of the beam. It is crucial to discretize the finite elements such that the average element size does not change from one model to the next which may cause a (perhaps substantial) difference in solution accuracy between coarse and fine elements, especially in plastic analyses. Therefore we use the same optimized mesh size for all models. Some important geometric details for the connection are shown in Table 1.

Description	Normal size	Over size
Plate depth h_p (mm)	260	260
Plate width w_p (mm)	100	100
Plate thickness t_p (mm)	10	10
Beam bolt-hole dia. d_{bo} (mm)	20	24
Plate bolt-hole dia. d_{po} (mm)	20	20

TABLE 1 – GEOMETRIC DETAILS OF SHEAR TAB CONNECTION

To establish contact within the bolts and other components of the connection in a numerical simulation, it is necessary to apply temporary boundary conditions (fixing bolts) to avoid rigid body movement which leads to numerical singularities. In a connection model, where bolt diameter exactly fits into bolt holes in either beam web or shear tab, applying such artificial boundary condition may not be necessary. However in a model with oversize bolt holes, the initial gap is significant and hence fixing the bolts becomes crucial to converge in the analysis. As shown in Figure 3, the bolt is initially placed to the top of the oversized bolt hole since the gravity loading will lead the components to that direction.

(A) NORMAL SIZE BOLT-HOLES (B) OVER SIZE BOLT-HOLES

FIGURE 3 – COMPARISON OF DIFFERENT BOLT SIZE MESHES.

3.2 Changing the bolt grade:

To avoid any brittle failure, it is necessary to make bolts strong enough to resist shear loads which, in addition to gravity, could be created by combination of moment (rotation) and axial forces (contraction/elongation) during a fire event. The effect of bolt strength is examined by reducing the strength of bolts by 40%, that is, by changing the grade from 8.8 to 5.6. Table 2 shows the material properties of these bolts where "measured" refers to test results [Lennon and Moore 2003; Wald et al 2006] and the Grade 5.6 values are nominal.

Model	Bolt Grade	Yield Strength (MPa)	Ultimate Strength (MPa)
Normal size	Grade 8.8	695 (measured)	869 (measured)
Oversize	Grade 8.8	695 (measured)	869 (measured)
Weak bolt	Grade 5.6	300 (nominal)	500 (nominal)

TABLE 2 – BOLT GRADES USED IN MODELS.

4. Results:

The FE results show that using oversize bolt-holes creates larger contact forces around the hole region throughout the analysis. If the bolt and bolt hole exactly fit to each other, as in the normal size bolt hole model, then the forces are uniformly distributed. For oversize bolt holes, the contact area gets smaller; hence the contact forces get larger. This idea is illustrated in Figure 4. This type of *non-smooth* interaction sometimes creates numerical convergence issues, which should be carefully studied during post-processing the results.

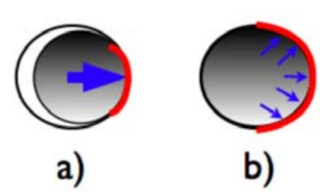
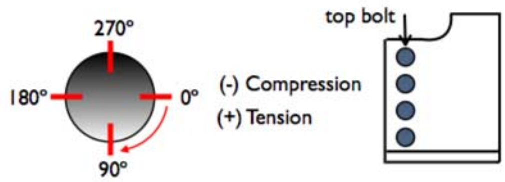
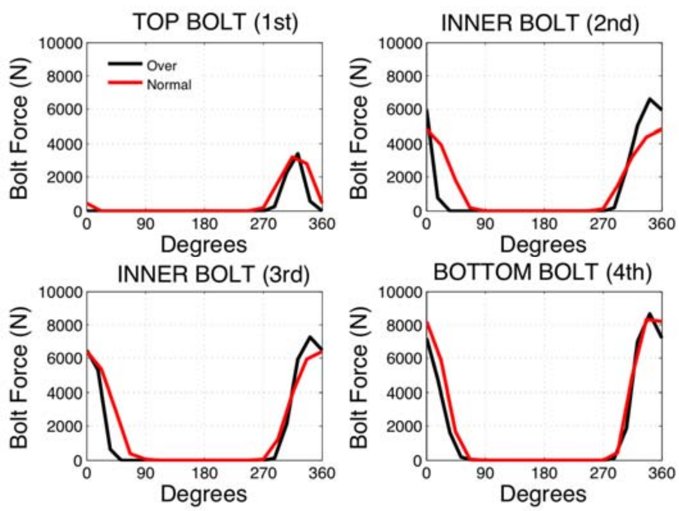


FIGURE 4 – CONTACT FORCES IN OVERSIZED (a) AND NORMAL-SIZED (b) BOLT REGION.

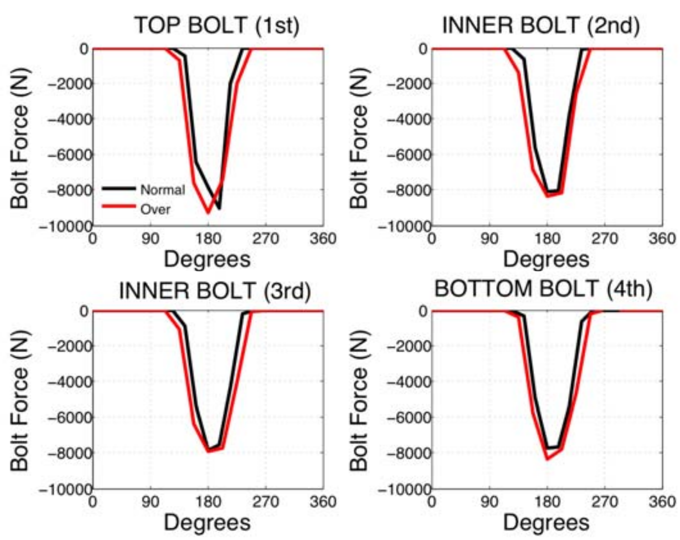
Figure 5 represents the forces around the circumference of the bolt hole at the beginning stage of the fire and near the end where positive values represent values consistent with the beam in compression. As expected, the location of bearing changes as the beam goes from compression to tension. Also, during the heating phase (Fig 5b) the peak contact forces are larger in some holes compared to others.



(a) SIGN CONVENTION



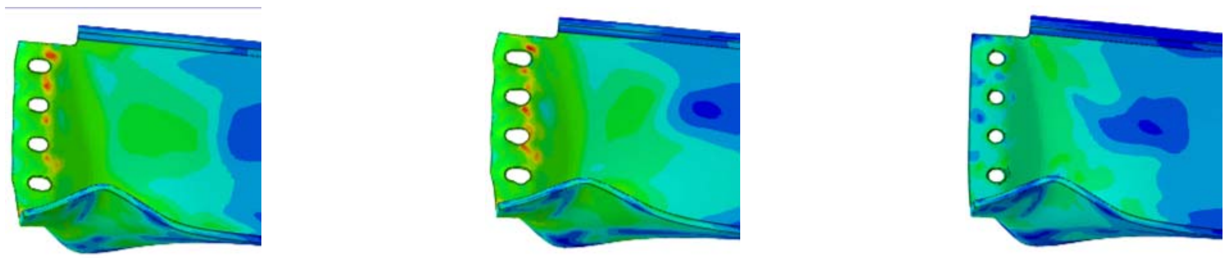
(b) ANALYSIS AT 15 MIN (DURING HEATING, REFER FIGURE 2)



(c) ANALYSIS AT 120 MIN (END OF COOLING, REFER FIGURE 2)

FIGURE 5 – CONTACT FORCES ALONG THE DIRECTION OF THE BEAM WEB (POSITIVE FORCES ARE CONSISTENT WITH COMPRESSION IN THE BEAM)

Overall, we find that modification on the size of the bolt region in the beam web does not change the limit state of the connection. Figure 6 shows the deformation in the beam web and bolts at the end of the analyses and it is seen by the large deformations in Figure 6(a) and 6(b) that the limit state is beam web bearing for both designs.



(a) NORMAL SIZE (b) OVERSIZE (c) WEAK BOLT

(d) GRADE 8.8 (normal size and oversize) (e) GRADE 5.6 (weak bolt)

FIGURE 6 - BEAM WEB DEFORMATION FOR ALL MODELS AT ANALYSES END (NORMALIZED MISES CONTOURS) AND EQUIVALENT PLASTIC STRAINS (PEEQ) FOR TWO GRADES OF BOLTS.

A modification of bolt material properties from Grade 8.8 to Grade 5.6 creates a change in the connection limit state. Previous studies with the original connection model [Garlock and Selamet 2009; Selamet and Garlock 2008] showed that no matter the fire scenario, the failure of the connection originated from beam web bearing. This failure is usually more favorable because of its ductile behavior. A more brittle limit state such as bolt shear occurs when the bolt Grade 5.6 is used in the model. Shear failure of bolts occurs during cooling phase when large tensile forces develop in the beam web. A simple Eurocode estimation to calculate the "joint tying resistance" for bolts in shear is as follows:

$$F_{v,u} = \alpha_v \; A_s \; \Phi \; f_{ub} = 55.1 \quad kN$$
$$N_{u1} = \sum_{n=1}^{4} F_{v,u} = 220.5 \; kN \qquad (1)$$

where $F_{v,u}$ is the ultimate shear resistance of a single bolt, α_v is 0.6, A_s is threaded bolt area (245 mm^2, ø (0.75) is the reduction factor for elevated temperatures, f_{ub} is the ultimate strength of bolt and n is the number of bolts. Kirby's [1995] suggests that 75% of f_{ub} will be left in the bolts at around 400 ^{o}C. This equation assumes that connected members are only in pure tension (no rotation in the connection) and bolts carry equal amount of tension before they fail. In a fire event, the connection is loaded with both large axial forces and moments, hence there will be some differences in bolt shear forces. However, the deformation and rotation of the connection towards the end of analysis suggests that equal distribution of tension to the bolts is a valid assumption for a single-plate connection as seen by the deformations in Figure 6(a) and 6(b). The theoretical limit state (220.5 kN) matches closely to the numerical result, which is 195 kN.

Table 3 summarizes the findings. All of the "failures" were during the cooling phase of the fire when the beam had a significant tensile force as illustrated in the table. The tensile force in the "weak bolt" analysis was smaller than the "normal size" or "oversize" analyses because the beam had not cooled as far as the other two since failure was reached sooner.

Model	**Limit State**	**End of Analysis*(min)**	**Avg. Beam Temp. at Failure (^{o}C)**	**Axial Force at Failure (kN)**
Normal size	beam web bearing	124	226	370
Oversize	beam web bearing	126	218	351
Weak bolt	bolt shear	100	407	195

TABLE 3 – SUMMARY OF RESULTS.

5. Conclusion:

This paper summarizes some preliminary results on modification on a single-plate connection model under fire conditions. The original connection details are based on the Cardington experiment [Wald et al. 2006]. A 3D finite element model employing contact mechanics allows analyzing the behavior of connection components separately. Previous studies by the authors show that this type of connection is vulnerable to fire due to tensile forces that develop during the cooling phase.

This study examined if using standard oversize holes in the connection would improve the response by allowing more free movement of the beam. The FE results show no significant delay in failure or any change in the limit state of the connection and oversize bolt-holes actually have higher contact forces in the hole region. The study indicates that standard oversize holes do not affect the response of the connection under fire since the amount of beam expansion, contraction, and rotation requires much larger hole size. The authors will examine if the necessary hole size to allow free movement of the beam is possible, given the constraints of construction and economy.

Another connection variation was Grade 8.8 versus Grade 5.6 bolts. The Grade 5.6 design failed in bolt shear (all four bolts) before the beam web started to show large deformation around the holes. The failure time decreased from 120 to 100 minutes. Further, the tension capacity of the subassembly has decreased by half from about 400 kN (beam web bearing) to about 200 kN (bolt shear). Such observations suggest using high-strength bolts for these connections to gain more strength.

This preliminary study provides some qualitative and quantitative insight into single plate shear connection design effects in a fire. The authors are currently expanding this work to include several more connection detail parameters so that cost-effective modifications to these single-plate shear connections can be proposed.

6. Acknowledgements:

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