Behavior of single-shear screw connections in steel sheeting in fire

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ABSTRACT: Corrugated steel sheets are normally attached to the underlying purlins or more commonly straight to the steel trusses by self-drilling or self-tapping screws. The behavior of sheeting connections in fire conditions is important because of the maximum compression force during thermal expansion and maximum tension force in catenary action exerted to the screw connectors at supports. In this paper, the performance of screwed connections between a thinner plate and a thicker plate are investigated to simulate the structural application of connecting the roof sheeting to underneath truss members. The investigations are carried out via both single lap shear tests and Finite Element (FE) modeling both at room temperature and at elevated temperature. The aims of this study are (1) to understand the failure mechanism of the screwed connection and (2) to get the load-displacement curves so that they can be used in the further research.

1 INTRODUCTION

The insulated metal deck roofing system is used for industrial buildings with low-pitched roof. The roofing system is mainly composed of three components: the steel sheeting itself, the insulation and fasteners or adhesive, and the weather resistant roof. The structural deck is the basis for each roofing system. The steel deck are manufactured with cold forming technique from thin steel strip and are attached to the underlying purlins or more commonly straight to the steel trusses by self-drilling or self-tapping screws.

It has been shown from researches (Sokol and Wald, 2006, Lu et.al., 2007) that axial forces can often be generated in fire in steel deck when the roof sheeting is loaded transversely and is connected to purlins or directly to the trusses with screw fasteners. Due to the restraints to thermal expansion these forces are initially compressive. At later stages the forces become tensile when the catenary action starts to develop, which helps the sheeting to survive in fire via behaving as a cable hanging from the adjacent structural member. If the large deformation of structure is allowed and the sheeting can survive in the large deflection stage in fire, the expensive fire protection can be removed or reduced due to wide covering area of the roof in this type of buildings.

One of the major factors affecting the steel sheeting behavior in fire is how the screw fasteners behave when they are used to connect steel deck to its supports. In this paper, a 3D finite element model for a single lap shear screw connection is created to simulate the behavior of connection of sheeting to roof truss in fire. This model considers the material nonlinearity, large deformation and contact behavior. The connection model is analyzed through the elastic and plastic ranges up to failure. This model can predict the ultimate resistance, deformation and stress distribution in con-
nections during fire. The model is calibrated by the testing and has been used to understand the failure mechanism of connections at both room and elevated temperatures.

2 SINGLE-LAP SHEAR TESTS

2.1 Testing set-up

The single-lap shear tests have been carried out to investigate behavior of the connection at elevated temperature. In the tests, 5-mm thicker plate and 0.8 mm thinner plate is connected with one screw connector to simulate the case when the sheeting is connected to the underneath truss member. The design of testing set-up is according to ECCS recommendations (2008). However, due to the size of the furnace available, the specimen designed based on ECCS has been reduced. The testing set-up, the specimen with Reduced Dimensions (RD) and the specimen with Standard Specimen (SD) are shown in Figure 1 (a), (b) and (c), respectively. Two groups of tests have been carried out: Group 1 is to validate the capability of specimens with RD; Group 2 is to test the specimens at elevated temperatures such as 200 °C, 400 °C and 600 °C. Since the displacement of the specimen inside furnace is recorded as the plate end displacement, measurement setting for SD specimens has been removed in the SD test as shown in Figure 1 (c).

In the room temperature tests, the rate of loading in the initial stage of testing shall not exceed 1 kN/min. Until the ultimate load is reached the rate of straining shall not exceed 1 mm/min (ECCS, 2008). The displacement control is used. At elevated temperatures, the tests are carried out in two steps. Firstly, the temperature is raised to a given temperature. Then the loading is applied to the specimen with the strain rate of 0.1% to 0.3% per minute. According to ECCS recommendations (2008), the maximum load is reached in a deformation of 3 mm in order to avoid the extra deformations in the connection. However, in fire case the large deformation is an alternative mechanism to avoid the failure of the structure. Thus, the tests have been stopped when the displacement of 20 mm is reached at room temperature and 15 mm at elevated temperature. The maximum load is recorded as the one in this range of deformation.

Figure 1. (a) Testing set-up at elevated temperature (b) Specimen with reduced dimensions (RD) (c) Specimen with standard specimen (SD).

2.2 Results for validation tests

In order to show the feasibility of testing results with RD specimens, a load-deflection curve is taken out respectively for SD and RD specimens as shown in Figure 2 (a). According to 7 points (0-6) marked on the curves, it can be seen that the deformation histories of two types of specimens are the same due to the same shapes of two curves. The maximum loads of the connections (point 5) are at about the same level. However, due to the displacement of SD specimen has been measured at the end of the plate instead of around the connection area, the RD specimens are more stiff than SD
ones. Figure 2 (b) shows the similar failure modes of the two types of specimens. It can be concluded that it is reasonable to use the specimens with reduced dimensions.

![Figure 2. (a) Load-displacement curves (b) Failure modes of SD and RD specimens](image)

2.3 Testing results at elevated temperatures

Due to the limitation of the testing furnace, the deformation histories of specimen at elevated temperatures cannot be observed. Only the final failure modes of the specimens are shown in Figure 3. Two failure modes have been observed: bearing and tearing failure of thinner plate below at 200 °C (a) and shearing failure of screw connector at 400 °C and 600 °C (b). The main factor that determines the final failure mode in the connection might be the relative material strength involved in the connections. At room temperature, the material strength of thinner plate is lower than that of screw connector. Thus the failure mode is Mode 1 failure. When the temperature is above 400 °C, the material properties for screw connector might drop dramatically because the ways of increasing of material strength to be used as screws (for instance heat treatment).

![Figure 3. Failure modes at elevated temperatures from testing and from FE analysis](image)

The deformation histories at room temperature are shown in Figure 4. It can be seen that the deformation of connection starts from the progressively curling or tilting of thinner plate because of the eccentricity of single lap shear joint (b). Then the slipping in the thinner plate is observed when the slipping is out of the cover of screw. The slipping is due to the local yielding of material when the bearing of screw fastener against thinner plate (c). Because of the large local strain, the cracking appeared in the thinner plate when the ultimate strength of material is reached. The tearing of thinner plate continues and in the later stage the base plate of screw cut into the thinner plates (d).
The load-displacement curves from tests are shown in Figure 4 (e). When comparing load-displacement curves at 20 °C to that at 200 °C, it can be seen that up to point 2 these two curves are very close because both strength and modulus of elasticity are not much reduced at 200 °C. Then load-deformation curves at 200 °C are higher than those of at 20 °C but with reduced ductility. The stiffness and maximum load at 400 °C and 600 °C are lower than those at room temperature because of the reduction of strength and modulus of elasticity of materials at elevated temperatures. The ductility has been reduced as well due to the brittle failure mode of screw connectors when comparing to the bearing tearing failure of thinner plate at 20 °C and 200 °C respectively.

![Figure 4](image)

Figure 4. (a), (b), (c) and (d) deformation histories; (e) load-displacement curves from tests and from FE modeling

3 FINITE ELEMENT MODELING

3.1 Structural modeling of connections

Figure 5 shows the structural assembly of the single-lap shear screw connection and connection details. Thinner sheet with thickness 0.8 mm simulates the steel sheeting in roofing system. The thicker sheet (10 mm) represents the top chord (structural hollow section) of the roof truss to which the sheeting is connected. The lengths of the two sheets are 150 mm, respectively. One screw connector Φ 5.5 mm x 26 mm with head diameter 11 mm is used to connect two sheets. The main function of screw thread is to prevent the screw from being moved along its axial direction, thus only three threads are modeled in order to improve the computational efficiency. The steel washer with diameter 15 mm is used between the screw connector and thinner sheet. The distances of centre of the screw connector to the sheet edges are both transversely and longitudinally 30 mm. Commercial FE software, ABAQUS/Explicit, is used as an analysis tool. Three dimensional eight nodes solid elements with reduced integration point (C3D8R) are chosen for modeling the thicker sheet, the thinner sheet, the screw, the screw thread and the washer. The description of mesh details and boundary conditions are presented in reference (Lu et.al, 2008).

The loading is applied to the connections as that in steady testing, i.e., the temperature first rises to a certain value and then the static load is applied. In this simulation, the loads are applied in three steps:

- Step 1: preload at 20 °C was applied between the steel washer and thinner sheet. This step attempts to simulate the stresses created when tightening the screw connectors. The analysis is carried out using shrink fit methods in ABAQUS/Standard. The results are imported to next two steps that are both carried out via ABAQUS/Explicit.
- Step 2: temperature rose to the given temperature (20 °C, 200 °C, 400 °C or 600 °C).
- Step 3: the displacement was applied to the right end of thin plates up to 20 mm along X direction.
3.2 Material modeling

In order to simulate the real behavior of material, true-stress and true-strain curves are used. Due to the high local strain in the thinner sheet in vicinity of screw connector, the progressive damage and failure of material are included in the analysis. From our trail simulations, it is assumed that the damage initiation starts when the equivalent plastic strain is 0.45 and the material failure is reached when the equivalent plastic strain is 0.5. The damaged elements are not removed from the analysis. The reduction factors for the yield strength and modulus of elasticity follow the values defined in the main text of EN 1993-1-2 (2005). The true-stress true-strain curves at elevated temperatures are shown in Figure 6.

Researches (Sokol and Wald, 2006) have revealed that failures normally do not take place in the screw connector itself. So the following assumptions are made in FE analysis: the screw connector has the higher strength and rigidity than other materials in the connection assembly. Therefore, the screw connector and washer have the linear elastic material properties with the same values of yield strength and modulus of elasticity as those of steel sheet at 20 °C. However, from our testing the failure of screw occurred at 400 °C and 600 °C. Thus, the material model of screw connectors needs to be modified in order to further apply the FE modeling. Therefore, in the following sections only results at 20 °C and 200 °C are compared.

4 VERIFICATION OF FE MODEL

Figure 3 shows that at 20 °C and 200 °C the failure modes from FE analysis is the same as those from testing results. Similar to 7 points in Figure 2, the load-displacement curves from FE analysis
at 20 °C and 200 °C can be divided also by 6 points up to maximum load (Figure 4). It can be concluded that FE model simulates the deformation history very well. Table 1 shows the comparisons of the maximum load from tests and from FE analysis. It can be seen that at 20 °C, the FE results are about 20% higher than testing results. At 200 °C, due to the differences of real material properties and model used in FE modeling, the maximum load values are the same but the ductility from FE analysis is larger than that from tests.

Table 1. Comparisons of maximum load and corresponding deformation from FE analysis to those from tests

<table>
<thead>
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<th></th>
<th>Test MaxLoad [kN]</th>
<th>Deformation [mm]</th>
<th>FE Analysis MaxLoad [kN]</th>
<th>Deformation [mm]</th>
<th>Comparisons MaxLoad (FE/Test)</th>
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<tr>
<td>20 °C</td>
<td>8.5</td>
<td>9.1</td>
<td>10.0</td>
<td>8.7</td>
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<td>200 °C</td>
<td>8.8</td>
<td>6.1</td>
<td>8.8</td>
<td>8.6</td>
<td>1.00</td>
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5 ANALYSIS OF FAILURE MECHANISM

The verified model has been used to understand the failure mechanism of connection at 20 °C and 200 °C. According to the 5 points in Figure 4, the following mechanisms at 20 °C are illustrated in Figure 6:

(1) The yielding of thinner plate due to the bearing of screw connector starts early, for instance, it has been observed at the deformation of 0.6 mm and initial slip happened due to material yielding (Point 1).

(2) Then the local buckling of thinner plate around screw connector has been observed at 1.2 mm (Point 2). However, in order to show it clearly, the deformation of 3.0 mm has been chosen. At the same time the thinner plate tilts due to the eccentricity of single lap shear connection.

(3) At point 3 (deformation of 3.6 mm or better to show with 4.2 mm), the buckling of the thinner plate has been observed.

(4) With the continuation of buckling, bending stresses appeared at the edge of thinner plate (ex. deformation of 7.2 mm). At point 4, the thinner plate slips out of washer.

(5) When the maximum load is reached (point 5), the material failure occurred. This can be seen from the reduction of bending effects at deformation of 8.4 mm.

(6) At deformation of 15 mm, it has been shown clearly the tearing of the thinner plate and the washer’s cutting into the thinner plate. The locations of maximum stresses have been transferred due to the tensioning of thinner plate.

The failure mechanism at 200 °C is similar to that described at 20 °C. The differences are as follows: (1) yielding of material occurred earlier (2) the maximum load is lower. These differences are due to the reduction of strength at elevated temperatures.
6 CONCLUSIONS

The test results have shown that (1) It is reasonable to use the specimens with reduced dimensions. (2) The failure modes of connections at room temperature is bearing and tearing failures of thinner plates. The maximum load is reached when the first tearing appeared in the thinner plate. (3) Two failure modes are observed at elevated temperatures: Mode 1 is the bearing and tearing failure of thinner plate at 200 °C; Mode 2 is the shearing failure of screw connectors at temperature equal or higher than 400 °C. (4) This failure mode can be avoided when using other type of connections such as shot-nailed connections. (5) The 6 points can be used to describe the load-displacement curves of connections at temperatures of 20 °C and 200 °C.

With the testing results, it has been shown that FE modeling can predict the behavior of connection well at 20 °C and 200 °C. The verified FE model has been used to understand the failure mechanism of the screwed connection at 20 °C and 200 °C.

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REFERENCES

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