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Finite Element Modeling of Single Lap Shear Screw Connection in Steel Sheeting in Fire

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Abstract: The load bearing steel deck is used in insulated metal deck roofing system for industrial buildings with low-pitched roof areas. The steel sheeting sections are manufactured with cold forming 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. The behavior of sheeting connections is important in fire especially when the sheeting is in catenary action and tensile forces are developed at supports where the screw connectors are located. A 3D finite element model is created using ABAQUS software to simulate the single lap screw connections connecting thinner sheet (0.8 mm) to thicker sheet (10 mm) under static shear at both room and high temperatures. 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. The analysis reveals that the failure modes of the connection for both room and elevated temperatures are bearing failure of the thinner sheet. The load bearing capacity of the connections depends on the friction between the washer and the thinner sheet, the direct bearing of the screw shank against the thinner sheet and the postbuckling resistance of thinner sheet. Degradation of material at elevated temperature further reduces the strength and stiffness of the connections. This connection model can be taken as a component model in the analysis of the behavior of steel sheeting system in fire, which is highly non-linear so as to save the computing time.

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 (Fig. **1**).

It has been shown from researches [1,2] that axial forces can often be generated in steel deck when the roof sheeting is loaded transversely and is connected to purlin or directly to the trusses with screw fasteners, in fire. 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 affects 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 connections during fire. If the model is calibra.ted by the testing, it can be integrated into the model created in previous research [2], i.e. predicting the behavior of transversely loaded sheeting in fire considering the real behaviors of connectors instead of assuming rigid connectors and no failure occurred in connectors. Additionally, this simple FE connection model can be taken as a component model in the analysis of the behavior of steel sheeting system in fire, which is highly non-linear so as to save the computing time.

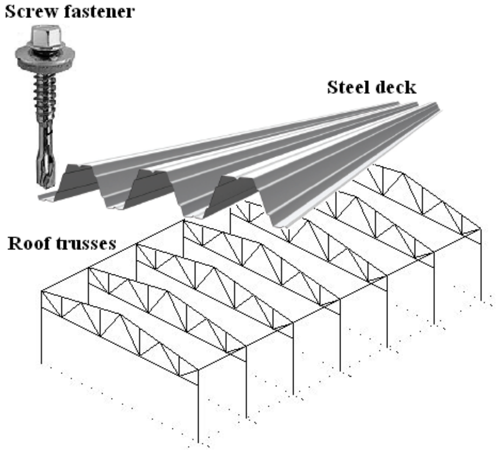

Fig. (1). Application of self-drill screw connector for connecting roof deck to roof trusses.

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STRUCTURAL MODELLING

Geometry of the Connections

Fig. (**2**) shows the structural assembly of the single lap shear screw connection and connection details. The connection assembly has followed the standard set-up for shear testing recommended by the E.C.C.S Committee [3] for the sake of the future testing. Thinner sheet with thickness of 0.8 mm simulates the steel sheeting in roofing system. The thicker sheet with thickness of 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, which are shorter than the single lap shear testing requirements. Because the deformation mainly concentrates on the local area of steel sheeting behind screws, thus the reasonable reduction of lengths of steel plates has little influence on the simulation results; and it will improve the computational efficiency.

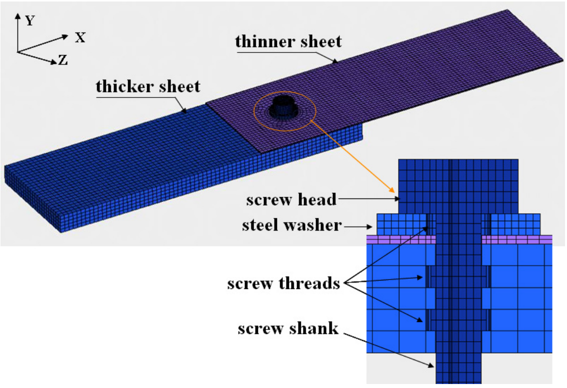


Fig. (2). Structural modeling of single lap shear screw connection and connector details.

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 of 15 mm and thickness of 2 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 according to requirements of testing set-up given by E.C.C.S. Committee [3].

FE Modeling

Commercial FE software, ABAQUS/Explicit, is used as an analysis tool. ABAQUS/Explicit is a special-purpose analysis product that uses an explicit dynamic finite element formulation and is suitable for solving the problems with converging difficulties because of the contact or material complexities [4]. The quasi-static analysis procedure was adopted with a small enough dissipated energy fraction so that the energy fraction has no effects on the behavior of connection assembly.

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. This element type is in the element library suitable for ABAQUS/Explicit analysis. Because of only one integration node in the thickness direction, instead of one layer of elements, more layers of elements are used along the thickness of thicker and thinner sheets.

The mesh densities in the two sheets in vicinity of screw connector should be refined due to the deformation mainly originating from this area and local buckling of the thinner sheet at a higher level of loading. However, using explicit method, the computational cost is proportional to the number of element and roughly inversely proportional to the smallest element dimension [4]. Thus, the smallest element dimension should be controlled so as to improve the computational efficiency. The steel washer is meshed because of the interests in the effects of changing of diameter of steel washer on the behavior of connections.

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 with value of 1700 N 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 given value (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 (Fig. **2**).

The boundary conditions are defined so that the left end of thick plates is fixed. The right end of thin plates can only move along the loading direction. The contact interfaces include the ones between the thinner sheet and the thicker sheet, between thinner sheet and steel washer, between the screw head and steel washer, between the thinner sheet and screw thread, between the thicker sheet and screw shank, and between the thicker sheet and screw thread. The contacts pair constraints are used to model the interactions of these contacts. In Step 1, kinematics contact pairs are used; in Step 2 and Step 3, the general contacts are used.

MATERIAL MODELING

From both our trial simulations and researches by Fan [5], due to the large ratio of thick to thin sheet thickness, the Von Mises stress in the screw vicinity of the thinner sheet exceeded the ultimate tensile strength of the material. This means that the material under tension stress already cracked but that under compression continues to function. To treat the local cracks 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.

In ABAQUS, the true stress and true strain curves are required when creating material model. The transformation of from nominal stress (σ_{nom}) and nominal strain (ε_{nom}) to true stress (σ_{true}) and true strain (ε_{nom}) are based on the following equations:

$$\varepsilon_{true} = ln(1 + \varepsilon_{nom}) \quad (1)$$

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \quad (2)$$

The material grades for two sheets are S350GD+Z, i.e. the yield strength is 350 N/mm^2 corresponding proof stress at 0.2% and the modulus of elasticity is 210 000 N/mm^2 at room temperature 20 °C. The reduction factors for the yield strength and modulus of elasticity follow the values defined in the main text of EN 1993-1-2 [6]. Fig. (**3**) shows true stress true stain curves including the damage rule at selected temperatures.

Researches [1, 5] have revealed that failures normally do not take place in the screw connector itself. So the following assumptions are made in the 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. The reduction factors for yield strength and modulus of elasticity follow the same value as defined in EN 1993-1-2 [6].

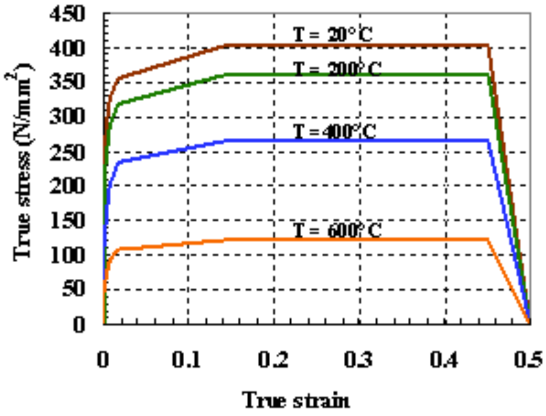


Fig. (3). True stress-true strain curves used in this analysis.

RESULTS AND DISCUSSION

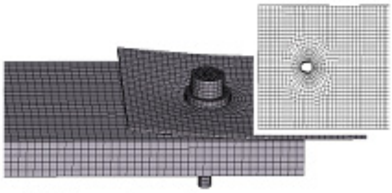
Failure Modes

Fig. (**4**) shows the failure modes of connection at 20 °C at various deformations. Because of the direct end bearing of the screw shank to the edge of thinner sheet around hole, the detail deformations of thinner sheet around hole are also provided in Fig. (**4**).

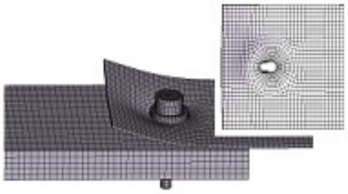
In the beginning of the deformation, due to the eccentricities of the applied load to the single lap shear connection, the bending of the thinner plates has been observed (deformation = 3 mm). With the increase of the applied load, yielding of the materials occurred. The yielding has been spread to form a yielding zone in the thinner sheet around the hole.

The local buckling of the thinner sheet has been observed in the bearing area of thinner sheet (deformation = 6 mm). Due to the post buckling strength of the thinner plates, the connections can still carry the load until local tearing failure of the thinner plate (deformation = 12 mm). Therefore, the connection failed due to the bearing failure of the thinner sheet. The spread of yielding zone and local buckling of thinner sheet will reduce the stiffness of the connections as well. Because of the degradation of the material strength, the load carry capacity of the connection will reduce with the increase of the deformation (deformation = 20 mm).

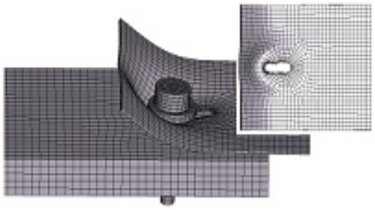
Fig. (**5**) shows failure modes of connection at 600 °C at various deformations. It can be seen that the failure modes at elevated temperatures are similar to those in 20 °C, i.e. connection failed due to the bearing failure of the thinner plates. The only difference is that the maximum load carrying capacity and stiffness of the connection will decrease due to the degradation of strength and stiffness of the material at high temperature. When creating the FE model, it has been assumed that no failure occurred in the screw connectors, which is true at room temperature. At elevated temperature, further testing is needed to verify the assumption.



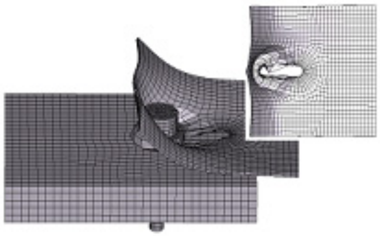
Deformation = 3 mm



Deformation = 6 mm

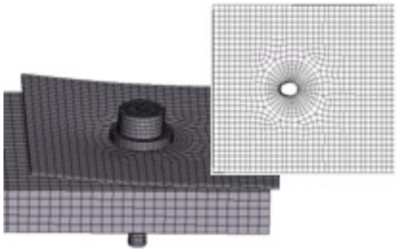


Deformation = 12 mm

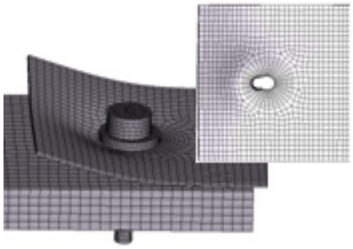


Deformation = 20 mm

Fig. (4). Failure modes at 20 °C at various deformations.

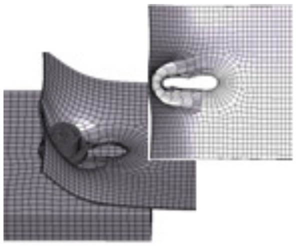


Deformation = 3 mm



Deformation = 6 mm

Deformation = 12 mm



Deformation = 20 mm

Fig. (5). Failure modes at 600 °C at various deformations.

Load Deformation Curves and Load Carrying Capacities

The load and deformation curves of connections at 20 °C, 200 °C, 400 °C and 600 °C are shown in Fig. (**6**). Since the deformation of the thicker sheet is small, so the output displacements are nodes displacements at the right end of the thinner sheet. Because fire is an accidental action, the design requires that the structure will not collapse in case of fire. In addition, catenary action of sheeting occurred in the large deformation. From these two points, the deformation is output up to 30 mm.

It can be seen that with the increase of temperature, both the strength and stiffness of the connections are reduced. The maximum strength of connection are reached when the tearing of the thinner plate is initiated. The maximum load and its corresponding deformation at elevated temperatures are shown in Table **1**. However, these values need to be verified with future testing before their further uses such as parametric studies of the effects of various factors on the behavior of connection; or this connection model is integrated into future research on understanding the roofing sheeting in fire.

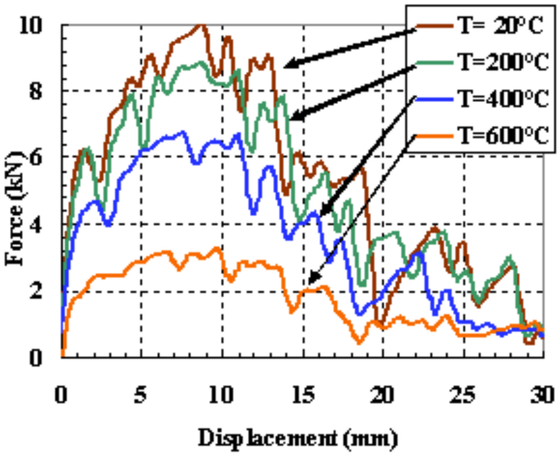


Fig. (6). Connection behavior at elevated temperatures.

Table 1. Maximum Loads and their Corresponding Deformation at Elevated Temperatures

Temperature [°C]	Maximum Loads [kN]	Deformations [mm]
20	10.0	8.9
200	8.8	8.9
400	6.7	9.5
600	3.2	9.8

The stiffness of connection starts to reduce when the slip is initiated at thinner plate because of the spreading of yielding zone. The stiffness is further reduced after the local buckling of the thinner plates. At elevated temperatures, the stiffness reduced further due to the degradation of the material.

In the trail simulation, we found out that the load bearing capacity also depends on the friction between the washer and the thinner sheet. According to Chung, the frictional forces are dependent on the clamping forces in connectors, the frictional coefficient between the contact surfaces and the sizes of washers [7]. The effects of these three parameters on the behavior of connection will be investigated further after the model being verified with the testing model. But we have investigated the effect of temperature on the value pre-load between the steel washer and thinner sheet. The results are shown in Fig. (**7**).

In the material modeling, the same materials have been used for steel sheets, the screw connectors and the washer. Therefore, the change of preload due to the thermal expansion can be neglected. The decrease of pre-load with the increase of temperature as shown in Fig. (**7**) is mainly caused by the material degradation at elevated temperatures.

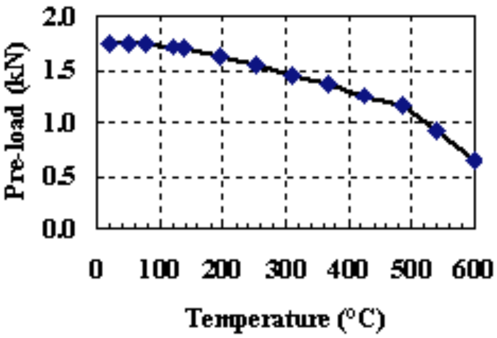


Fig. (7). Variation of preload with variation of temperatures.

CONCLUSIONS

3D finite element model incorporating geometric non-linearity, material non-linearity and contact interaction have been created to predict the failure mechanism of a single shear lap screw connection in both room and elevated temperatures. Due to the large local strain at the thinner sheet near the hole, the strength degradation of the material has been incorporated into the material model.

FE analysis reveals that the failure modes of the connection for both room and elevated temperatures are bearing failure of the thinner sheet. The load bearing capacity of the connections depends on the friction between the washer and the thinner sheet, the direct bearing of the screw shank against the thinner sheet and the post buckling resistance of thinner sheet. The stiffness of the connection are reduced due to the initiation of slip of thinner plate and further reduced because of local buckling of thinner plate and degradation of material at elevated temperature. The maximum loads are taken at larger deformation due to the fire being an accidental action.

The FE model needs to be calibrated via testing before it can be used further for parametric investigation or incorporated into the roof sheeting system for investigating the behavior of sheeting in catenary action in fire.

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