FE Model Validation and Advanced Analyses of Steel Members with Steel Claddings at Elevated Temperatures

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Abstract

In order to investigate the stabilization effect of distinct steel members by steel cladding system including trapezoidal sheeting and sandwich panels in fire using advanced analysis techniques, the computer models and modeling techniques must be validated by available experiment tests. However, the fire tests in this area are scarce. As part of a wider validation scheme, this paper presents the modeling method using Ls Dyna explicit solver and the comparison of FE analysis results with four experimental tests at elevated low to medium temperatures (150-300 °C) in RFCS STABFI project. After the model validation, the advanced fire analyses of steel columns with two types of steel claddings such as trapezoidal sheeting and sandwich panel are carried out to investigate the stabilization effect. The analyses show that for the studied I-section column under both axial compression and bending moment, the position of steel claddings, either connecting with the tension flange or the compression flange, has significant influence on the fire resistance of the steel column. When the trapezoidal sheet is connected with the compression flange, the fire resistance of steel column is 17 % more than that without cladding. Sandwich panel cladding has influences on the deformational behavior of column during the fire exposure. However, the contribution of sandwich panels to the fire resistance of steel columns is negligible due to the delamination of inner panel sheet.

Keywords

FE model validation, advanced fire analysis, steel column, steel cladding, elevated temperatures, trapezoidal sheet, sandwich panel

1 Introduction

Studies has shown that there is a significant stabilization effect of steel structures by the steel claddings including sandwich panels and trapezoidal sheets [1-3]. There is a strong interest on the stabilization effect in case of fire. The project STABFI (Stabilization of Steel Structures by Steel Claddings in Fire) addresses this research question. Both experimental tests and structural fire analysis are conducted to investigate the stabilization effect of steel structures by the building envelopes including sandwich panels and trapezoidal sheets.

The fire tests for the stabilization research of steel columns by sandwich panels are challenging due to the presence of large amount of smoke when the temperature exceeds 300 °C. Furthermore, the panel sheet will delaminate as well from the insulation core when the temperature exceeds 200-300 °C [4]. Therefore, the tests described in this paper were performed with a maximum temperature of 300 °C.

In this paper, the modeling method, material properties of steel profiles with two steel cladding systems and the equivalent properties of fasteners are validated using Ls-Dyna [5] by the available tests in RFCS STABFI project. Four tests for the steel columns restrained by trapezoidal sheeting and sandwich panels at both ambient temperature and medium temperature (150-300 °C) are simulated and the results are compared with the test measurement. Together with two additional validation efforts, including the FE modeling of steel columns stabilized by sandwich panels at normal temperature [6] and structural fire analyses of steel structures in fire without claddings [7], the confidence is gained on the structural fire analyses of steel structures with steel claddings in fire. Advanced structural fire analyses are performed to investigate the stabilization effect of steel claddings on the column in case of ISO fire.

2 FE model validation

2.1 Description of fire tests

Experimental tests with different steel column profiles and cladding systems were carried out by Joo et al [8]. In this paper, four tests
were simulated in order to validate the modeling methods and parameters using Ls-Dyna. The steel profile is HEA160 with a grade of S355. The cladding systems of Ruukki T153 trapezoidal sheeting and SPA230 sandwich panel with mineral wool core were tested.

The overview of the test set-up is illustrated in Figure 1. The overall dimensions of test specimens are 3.0 m x 3.0 m (cladding size), where the spacing of the three hot rolled steel columns is 1.5 m. The steel claddings are installed on the outer face of steel columns.

A loading frame was erected in order to provide the loading force to the simply supported middle column of the specimen. The two columns on the side of the panels were restrained in vertical direction, so they were able to move horizontally. Two symmetrically placed hydraulic jacks were fixed to one end of the loading frame, to provide an increasing load to the middle column.

In addition, an additional hydraulic jack was installed eccentrically to the middle member, providing eccentric load in the specimen. In these cases, in addition to the axial load, an additional bending moment was applied. The eccentric load was set to 10 % of the actual axial load and was applied 75 cm above the middle column. The eccentric hydraulic jack was positioned above the specimen, so the outer face of the panel was in tension.

The test was carried out at ambient temperature or elevated temperatures. A system of ceramic heating pads was used to heat the steel claddings and the middle column. The middle column was considered to be fire protected. The temperature in HEA160 is 150°C and 300°C for the trapezoidal sheeting or inner face of panel sheet, in the studied cases in this paper.

The steel grade for the columns is S355 and S350 for T153 sheet. Up to the completion of analyses, no actual tensile testing data for these materials are reported, therefore the data from literature [3][10][11] are used. Tri-linear material model is defined for 20°C cases, and piecewise-linear material model is used for 150°C case (according to EN1993-1-2[9]). The material models used in the analysis for S355 is shown in Figure 3. According to Yun and Garner [11] and Outilen [11], the actual yield strength for S355 hot rolled profile could be between 410 - 460 MPa. Therefore, two analyses with yield strengths of 410 MPa and 450 MPa were performed for each case. Recently, the tensile test is conducted for the flange of HEA160 and the measured yield strength is 463 MPa. The true stress-strain curve for T153 sheeting is illustrated in Figure 4.

Pinned boundary conditions are defined around two axes in the cross section for the central nodes of constrained rigid bodies at both ends of the middle column. Fixed boundary is defined along the longitudinal direction of column axis in one end of the middle column, in the end of loading beam; in another end of the middle column, keyword *boundary_prescribed_motion_node is used to define the displacement loading along the longitudinal axis of column, in the end of loading beam. Restraints in the vertical direction are defined for the edge columns at ¼ and ¾ length positions.

Geometrical imperfections and initial stresses are not included in the original models due to the large loading eccentricity. The effect of the geometrical imperfections and initial residual stresses on the load-displacement curve is given in Section 2.4.

2.2 FE models

2.2.1 HEA160 with T153 cladding

The FE model for HEA160 profile with T153 sheeting is shown in Figure 2. Quadrilateral shell elements with reduced integration are used for both steel columns and T153 sheeting. For steel columns, the element size is around 20 mm in cross section and 40 mm along the length; for T153 sheeting, the element size is 20 mm in lower troughs of profiled section and 40 mm for the other dimensions. Constrained rigid bodies are defined for both ends of the middle column where the load is applied. Two beam elements are defined in both ends for applying the eccentric load and the eccentricity is 75 mm. Displacement-controlled loading approach is used. Ls-Dyna R971 is used for the analyses.

Figure 1 Test arrangement at ambient temperature (Joo et al 2019).

Figure 2 FE model of HEA160 profile with T153 sheeting.

Figure 3 Material models (S355) for HEA160 profile.

Figure 4 Material models for sheeting and steel face of sandwich panels.

One self-drilling screw is used per rib. The temperature dependent...
properties are obtained from Lu et al (2012). In Ls-Dyna, the discrete beam element does not have temperature-dependent spring properties. Equivalent Hughes-Liu beam element is used to simulate the shear behavior of the fastener under elevated temperatures. An equivalent cantilever beam model with 10 mm length was created and the material properties of MAT4 (keyword: ‘Elastic_plastic_thermal’) of equivalent beam was correlated with the lap shear behavior of fastener test. The diameter of equivalent beam is selected based on Timoshenko beam theory and the diameter of equivalent beam for shot nails is 5.4 mm in these models. The material properties of the equivalent beam for 5.5 mm shot nails are shown in Table 1.

| Shotnail –Equivalent Beam, MAT4, Elform=1, d=5.4 mm, L=10 mm | E (MPa) | fy (MPa) | Etan (MPa) |
|-------------------------------------------------------------|---------|----------|------------|
| T=20 °C                                                     | 50 000  | 1140     | 500        |
| T=200 °C                                                   | 40 000  | 1560     | 100        |
| T=400 °C                                                   | 40 000  | 990      | 0          |
| T=600 °C                                                   | 20 000  | 220      | 0          |

Figure 5 illustrates the corresponding force versus displacement responses of a single equivalent beam at elevated temperatures. Material data from Table 1 are used to obtain these curves. These curves simulate the lap shear behavior of 5.5 mm screw at elevated temperatures by Lu et al [12] in an approximate way.

2.2.2 HEA160 with SPA230 cladding

Figure 6 illustrates the FE mesh for HEA160 profiles with SPA230 sandwich panel claddings. The modeling of HEA160 columns are the same as previous case, with extra consideration of fillet radii (15 mm) in the junction of flanges and web. Element thickness is increased 1 mm in the junction area to take the fillet corner radii into account. Without this, the cross section of HEA is class 2, local buckling may occur after yielding.

Sandwich panels are modeled using solid elements for mineral wool core, glue layers and thin shell elements are used for steel faces. The in-plane element size is 80 mm in panel length direction and 40 mm in panel width direction. In thickness direction, element size of core is 40 mm.

Elastic material model is used for the mineral wool core. A constant elastic modulus of 6 MPa is defined and Poisson’s ratio is zero. Modified Johnson–Cook model is used for glue layer. Material properties of glue layer is intentionally defined the same as mineral wool core. The melting temperature of glue layer is 300 °C. At and after this temperature, the delamination between steel face and mineral wool core will occur.

Automatic surface-to-surface contacts are defined between panels and upper flanges of steel columns, as well between panels.

The long self-drilling screw is modelled by two parts: the lower spring part simulating the hole-elongation of lower face and the link between lower face and upper face, to provide the axial restraint. Equivalent Hughes-Liu beam element is defined for spring part. Beam element is defined for the link part (screw shank) but the rotational restraints in lower node are released, so that pinned connection exists between spring part and link part.

Geometrical imperfections and initial stresses are not included in the original models due to large loading eccentricity. The effect of these imperfections on load-displacement curve is given in Section 2.4.

Three self-drilling screws are used for each sandwich panel to connect with the flange of steel column and the equivalent material properties of spring part are found based on the behavior of translational stiffness testing results in Wald et al (2018). The fictitious equivalent properties of self-drilling screws for sandwich panels are listed in Table 2.

| Screws –Equivalent Beam, MAT4, Elform=1, d=3.2 mm, L=10 mm | E (MPa) | fy (MPa) | Etan (MPa) |
|----------------------------------------------------------|---------|----------|------------|
| T=20 °C                                                   | 50 000  | 2000     | 0          |
| T=300 °C                                                  | 40 000  | 1800     | 0          |
| T=450 °C                                                  | 32 000  | 1500     | 0          |
| T=600 °C                                                  | 20 000  | 1000     | 0          |

The corresponding force versus displacement curves of a single equivalent beam for self-drilling screws at elevated temperatures are shown in Figure 7. The material data in Table 2 are used in obtaining these curves. These curves simulate the translational lap-shear behavior of 5.5 mm self-drilling screw for sandwich panels at elevated temperatures by Wald et al [15] in an approximate way.
2.3 FE model validation

Figure 8 illustrates the comparison of FE analyses with test for T153 cladding at 20 °C. Two analyses were performed: one with yield strength of 410 MPa for steel profile and another of 450 MPa. The abscissa is the out-of-plane (along minor axis) displacement of middle column at mid-span, and the ordinate is the eccentric axial load (10% of total axial load). It can be seen that the stiffnesses of middle column before yielding have good agreement between analyses and test. For the maximum force, the case with 410 MPa yield strength is 7% lower than the test, and the case with 450 MPa is the same as test. In the declining phase, test result is faster than FE analyses.

Figure 9 illustrates the results for T153 cladding at 300 °C. It can be seen that the stiffnesses of middle column before yielding have good agreement between the analyses and the test. For the maximum force, the case with 410 MPa yield strength is 9% lower than the test, and the case with 450 MPa is the only 2% lower than the test. In the declining phase, test result is similar to the FE analyses. There are differences in the displacement corresponding to the maximum loads.

Figure 10 shows the comparison for HEA160 columns with SPA230 cladding at 20 °C. The slope of load-displacement curve before yielding of middle steel column agrees well with the test. The maximum load for fy=410 MPa by FE analysis is 12% lower than the test, and the one for fy=450 MPa is 7% lower. In the declining phase, the load from the test decreases faster than the FE analyses.

Figure 11 shows the comparison for HEA160 columns with SPA230 cladding at 300 °C. The slope of load-displacement curve before yielding of the middle steel column agrees well with the test. The maximum load for fy=410 MPa by FE analysis is 5% higher than the test, and the one for fy=450 MPa is 12% higher. In the declining phase, the slope of the testing curve is similar to the FE analyses.

2.4 Effect of imperfections

In order to see the effect of imperfections on the FE analysis results,
Advanced structural fire analyses

Steel cladding systems such as trapezoidal sheeting and sandwich panels can provide significant stabilization effect on the stability of steel columns or beams at ambient temperature [2-3][6][16]. Usually the steel claddings can provide sufficient lateral restraint to prevent the buckling around minor axis and therefore increase the load-bearing capacity of steel columns or beams. In case of fire, the cladding system is usually unprotected, and the temperature increase rapidly due to its thin thickness. The fasteners connecting cladding elements and steel members will also undergo rapid increase of temperature. Therefore, the stabilization effect of the same cladding system in case of fire is under investigation.

In this section, the structural fire behavior of a steel column with steel claddings will be compared with those without claddings. The contributing effects of trapezoidal sheeting and sandwich panels on the fire resistance of structural members under standard ISO fires are studied using LS-Dyna. The virtual test arrangement is according to the test arrangement in [3], and the column or beam spacing is 6.0 m, under ISO fire. The profile dimension of the column and the load ratio are determined according to the reference design of a one-storey portal framed industrial building in RFCS Stabfi project [17]. The advanced analyses include temperature analysis and structural analysis for each case.

3.1 Structures and loads

The structures are selected according to the design calculations of portal frame solution of reference building carried out in [17]. The column profile is HEA600 (S355) and column spacing is 6 m. Column length is 10 m. Both ends are pin-supported. Between two columns, there are trapezoidal sheeting Ruukki T153 or Sandwich panels SPA230. The loads in case of fire are calculated according to Eurocodes (EN1990 and EN1991-1-2) for the reference portal frame. The internal forces in the columns of middle frames for most unfavorable load combinations are used in the following FE analyses. The axial load N is 133.54 kN and bending moment around the axis of greatest inertia is 538.0 kN-m. Axial load and bending moment are applied on the top end of column. The corresponding load ratio is 0.28.

The thickness of T153 steel sheeting is 0.9 mm and the steel grade is S350. The nominal thickness of internal face of SPA230 is 0.5 mm and that of external face is 0.6 mm, and the steel grade is S280.

3.2 FE models for structural fire analyses

3.1.1 HEA600 with T153 claddings

The FE model is illustrated in Figure 14. It should be noted that the Y-axis is along the longitudinal axis of columns, Z-axis is the strong axis of inertia of the steel section, and X-axis is the weak axis of the cross section. This is also the same for the following SPA230 cladding cases.

The FE model is created using Belytschko-Tsay thin shell elements for steel profile and trapezoidal sheeting. The element size for the steel profile is 40 mm. The element size is selected according to the studies in Ma et al [7]. The element size for steel sheeting is 40 mm in the regions above steel flanges, and 40x80 mm in the mid-region between steel columns. LS-Dyna keyword *Constrained_rigid_body are defined in the ends of the steel columns in order to apply the pinned boundary conditions and the loads. 10 mm long beams are defined to model the eccentricity of axial load, to take the geometrical imperfection (L/1000) of the steel column into account. The bending moment is applied around the axis of the greatest inertia (z-axis) in the center of the rigid body (Figure 15).

Three fasteners are defined per trough in the model. The modeling method and temperature-dependent properties are same as described in Section 2.2.1.
Temperature-dependent stress-strain curves and thermal expansion coefficient of steel are taken according to Eurocode EN1993-1-2 [9].

A simple 2D temperature analysis is performed to obtain the temperature histories of the steel profile with trapezoidal sheet (with 200 mm thick mineral wool insulation board on top of the sheet). Further details on the model method for temperature analysis can be found in Ma et al [18]. Figure 16 shows the temperature development when the structure is directly exposed to the ISO standard fire. The non-uniform temperatures are applied to the steel columns and uniform temperature to the trapezoidal sheet as thermal loads.

### 3.1.2 HEA600 with SPA230 cladding

The element type and size for the steel columns are the same as the above case. The sandwich panels are modeled by thin shell elements for steel faces and solid elements for mineral wool (MW) core (Figure 17). The in-plane element size is 160 mm. The size in thickness direction for MW core is 60 mm and there are four layers in thickness direction of core. The element size is smaller than previous study at ambient temperature by Ma et al [6].

Three self-drilling screws are used for each sandwich panel to connect with the flange of steel column. The modeling method and temperature-dependent properties are same as described in Section 2.2.2.

Figure 18 shows the temperature histories of HEA600 profile with sandwich panel SPA230 on the top. The temperature history in the inner panel sheet is shown in Figure 16b. Temperature input is defined using "Load_Thermal_Variable" keyword. The temperature histories of top and lower flanges at one quarter of flange width are used as the average temperatures in the flanges. The temperature history at the center of web is used for the web.

Based on many fire tests on sandwich panels, the adhesives between inner steel face and MW core will melt at 200 – 300 °C and delamination between steel face and core will occur [4]. A thin glue layer is defined between the steel face and the core. In order to simulate the delamination behavior during fire, material model MAT_107 (keyword "MAT_Modified_Johnson_Cook") is used with similar properties as MW and delamination temperature of 300 °C.
3.3 Structural responses

3.3.1 HEA600 with T153 cladding

In this case, either the tension flanges (Mz+) or the compression flanges (Mz-) of steel columns are connected with T153 cladding. Mz+ corresponds to that the positive bending moment is applied around z-axis, and Mz- corresponds to the negative bending moment in addition to axial compressive force N.

Figure 19 illustrates the lateral displacement of compression flange at a distance of ¼ length of steel column from the top end. It can be seen that, for cladding in the tension flanges side (Mz+), the lateral displacement of compression flange is larger for the case with T153 cladding than the case without cladding. For the bending displacement along x-axis in the same position, it is also larger for the case with the cladding than without the cladding until collapsing (Figure 20). This is due to the fact that the sheeting has faster temperature rise than the HEA600 profile. The thermal expansions of sheeting produces pushing forces along z- and y-axis, which result in larger lateral and bending displacements.

The fire resistance is 22.3 minutes for the case with T153 cladding in the tension flange and 21.7 minutes for the steel column without cladding. The fire resistance of the case with T153 cladding is slightly longer than that without cladding.

For the case with the cladding in the compression flange side (Mz-), the collapse of steel columns is mainly due to the excessive bending and the axial loading, not lateral-torsional buckling of the steel column due to the fact that the compression flanges are restrained by T153 cladding. The fire resistance of the steel columns with cladding is 25.7 minutes and that without cladding is 22.0 minutes. T153 cladding connecting with compression flanges of the HEA600 profile provides the stabilization effect on the steel columns and 14% longer fire resistance.

Figure 21 shows the shear force development in the fasteners along the z-axis with the specified distance from the top end, for the case of cladding in compression flange. It can be seen that the first fastener which have a distance of 300 mm obtains the largest shear force. With the increasing distance from the top end the obtained shear forces become smaller till the middle of column height. Table 3 shows the maximum shear force developed in the first fastener versus fire exposure. The corresponding shear capacity of the fastener is also listed in the table. In this table, the numbers in the parentheses indicate the time and maximum shear forces for Mz- case. The time to reach the maximum shear force in the first fastener is slightly different for both cases.

Table 3 Maximum resultant shear forces in the fasteners versus fire exposure duration.

| ISO fire duration (min) | Average temperature in shot nail (°C) | Max. shear force (kN) (Mz+ case) | Max. shear force (kN) (Mz- case) | Max. shear capacity (kN) |
|------------------------|---------------------------------------|----------------------------------|----------------------------------|-------------------------|
| 1.7 (2)                | 120 (210)                             | 6.16 (6.60)                      | 8.50 (8.8)                      |
| 5                      | 280                                   | 3.80                             | 3.85                             | 7.66                    |
| 10                     | 405                                   | 2.50                             | 2.13                             | 5.80                    |
| 15                     | 480                                   | 1.60                             | 1.15                             | 3.93                    |
| 20                     | 565                                   | 1.00                             | 0.66                             | 1.95                    |

Table 4 summarizes the fire resistance of steel columns with T153 cladding. The critical deflection criteria is widely used in assessing
the fire resistance tests of structural elements. In this study, the limiting deflection rate of $L^2/9000d$ (where $L$ is the span length and $d$ is the height of cross section) by European testing standard (EN1363-1) and classification standard (EN13501-2) is used to determine the fire resistance. It can be seen that the fire resistance is only slightly longer when the T153 cladding is in the tension flange, and 17% longer when the T153 cladding is in the compression flange.

Table 4 Summary of fire resistances for HEA600 with T153 cladding.

| Column or beam profiles | Cladding system | Fire resistance (min) |
|--------------------------|----------------|----------------------|
| HEA600, cladding in tension flange | w/o cladding | 22 |
|                         | T153          | 22.3 |
| HEA600, cladding in compression flange | w/o cladding | 22.0 |
|                         | T153          | 25.7 |

3.3.2 HEA600 with SPA230 cladding

Figure 22 illustrates the lateral displacements of columns at compression flange at a distance of ¼ column length from the top end. Lateral displacement is much larger when the SPA230 sandwich panels are connected with the tension flange (Mz+) than without sandwich panel cladding. It can be seen that there is an adverse effect on the deformational behavior of steel column when the SPA230 is in the tension flange. Delamination of inner face of SPA230 occurs at 9.5 minutes, which corresponds to the temperature of 300°C at glue layer. Similar behavior is observed also when the SPA230 cladding is connected with the compression flange. However, the lateral deformation is closer to the case without cladding before the runaway.

Figure 23 illustrates the bending displacement along the x-axis. The bending displacement is also larger than without sandwich panel cladding. The fire resistance is 22 minutes for both the column with cladding and the column without cladding. Therefore, there is no stabilization effect by the sandwich panels observed in this case. This is due to the high temperature and delamination of inner face of sandwich panel.

Figure 24 shows the shear forces of the screws during direct fire exposure. The fastener’s force is relatively small and obvious oscillation can be seen. Dynamic explicit solver is used for the analysis. Rapid thermal expansion and delamination of inner steel face cause dynamic oscillation in the fastener shear forces. Shear forces of screws are relatively small and therefore the oscillation effect is relatively significant. The maximum resultant shear force is around 1.3 kN at 4–6 minutes. However, the axial force is relatively large. The maximum tension force is 12.3 kN before panel face delamination.

Figure 22 Lateral displacement of compression flange at ¼ length from top end – SPA230 cladding.

Figure 23 Bending displacement of compression flange at ¼ length from top end – SPA230 cladding.

Figure 24 Shear forces of two corner screws at third panel from top.
According to the translational tests by Wald et al [15], the maximum loading capacity of 5.5 mm self-drilling screw is shown in Table 5 for SPA230 with 10 mm flange thickness.

Table 5 Maximum shear capacity of 5.5 mm screw for SPA230 with 10 mm thick flange [5]

| Temperature (°C) | T=20 | T=300 | T=450 | T=600 |
|------------------|------|-------|-------|-------|
| Shear capacity (kN) | 1.40 | 2.90  | 2.30  | 0.75  |

Table 6 summarizes the fire resistance of HEA600 profile with SPA230 cladding. The contribution by sandwich panel to the fire resistance is negligible for all cases. There is an adverse effect on the deformation behavior of steel column by the sandwich panel in fire.

Table 6 Summary of fire resistances for HEA600 with SPA230 cladding.

| Column or beam profiles | Cladding system | Fire resistance (min) |
|-------------------------|-----------------|----------------------|
| HEA600, cladding in tension flange | w/o cladding | 22.0 |
|                          | SPA230          | 22.0                 |
| HEA600, cladding in compression flange | w/o cladding | 22.0 |
|                          | SPA230          | 22.3                 |

3.3.3 Effect of delamination of inner sheet in sandwich panel

In order to observe the effect of non-delamination of inner panel sheet on the fire-resistant behavior of the steel column, one additional analysis is performed. In this case, the delamination of SPA230 inner face at 300 °C is deactivated. Perfect bond is assumed between inner steel face of sandwich panel and mineral wool core. The sandwich panels are connected with the compression flange (Mz-).

Figure 25 illustrates the lateral and bending displacement of steel column at a distance of ¼ column length from the top end. It can be seen that the lateral deformation is smaller when there is no delamination, and the fire resistance of 23 minutes is slightly longer. The effect on the bending displacement along x-axis is very little. It can be concluded that the sandwich panel cladding has small stabilization effect to the steel columns in case of fire in this case, due to the rapidly increased temperature in the inner face. At 20 minutes, the temperature in the inner face of SPA230 is 736 °C (Figure 16b).

4 Conclusions

The modeling method for steel profiles with trapezoidal sheeting cladding or sandwich panel cladding are verified at ambient temperature [6]. For the steel structures under fires, the structural fire analysis procedure using Ls-Dyna is developed and validated by Ma et al [7]. The FE modeling of steel structures with steel claddings such as trapezoidal sheets and sandwich panels at medium temperature is validated in this paper. The agreement between the simulation results and tests are fairly good. The delamination of panel face and mineral wool core at 300 °C is verified in the case with the SPA230 sandwich panel cladding. The modeling method for self-drilling screws and equivalent properties are verified as well.

Structural fire analysis procedure from temperature analysis to structural response analysis is verified based on the case studies for simple steel structures in Ma et al [7]. The model for the structural fire analysis at elevated temperature beyond 300 °C for claddings are not directly verified due to the lack of structural fire tests at the moment. However, higher confidence can be obtained on the modeling method, material properties at elevated temperature, equivalent properties of self-drilling screws at elevated temperatures based on the present studies in this paper. Furthermore, advanced structural fire analyses are performed to study the behavior of a beam-column with HEA600 profile with steel claddings under fire.

For the HEA600 columns directly exposed to fire, when the cladding
is connected with tension flanges, the fire resistances with and without T153 claddings are very close to each other. The stabilization effect by trapezoidal sheeting is negligible. When the cladding is connected with the compression flanges, the fire resistance with T153 cladding is 17% more than that without cladding. The stabilization effect is obvious in case of fire.

The sandwich panel cladding has influences on the deformational behavior of the steel column during fire exposure, for the case without fire protection. The contribution by sandwich panel to the fire resistance is negligible for all cases. There is adverse effect by the sandwich panel in fire on the lateral deformational behavior of steel columns.

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