Numerical investigation of instabilities of steel members restrained by sandwich panels at elevated temperature

Anita Lendvai¹, Attila László Joó²

Abstract

Sandwich panel constructions are getting popular from the second half of the 20th century however, the restraint provided by sandwich panels in regards to the instability of structural members was not investigated at elevated temperature, which became the scope of the research introduced in this paper. An experimental test series was conducted at the Department of Structural Engineering at the Budapest University of Technology and Economics in order to study the stability behavior of structural members restrained by sandwich panels at ambient and elevated temperature. In this paper 18 tests are introduced, in which centrally located HEA120 sections of a 3.00 m x 3.00 m sized supporting sandwich panel diaphragm were tested for axial compression. The results indicate, that the decrease in load bearing capacity of PIR panels is higher, that in the case of mineral wool panels. The data derived from experimental tests were used for developing a complex numerical model. The primary objective of this paper is the comparison of numerical results with the results derived from experimental testing. This research has been financially supported by the European Union, in the frame of the Research Fund of Coal and Steel (RFCS) program. The authors gratefully acknowledge the support.

Keywords

Sandwich panels, Buckling, Numerical model, Elevated temperature

1 Introduction

1.1 Overview of international studies

From the middle of the 20th century research work started internationally to investigate the stiffening effect of assembled systems of profiled sheeting for in-plane shear.

The first full-scale experimental portal frame tests were carried out in 1973 by Bryan [1], in which the stiffening effect of sheeting was observed, and the term "stressed skin effect" can be originated. In the following years extensive research started by Bryan and Davies in state of art, and the first design expressions regarding stressed skin design were developed and detailed in ECCS proposals [2], and became model for other codes [3]. Although several studies were established investigating the stiffening effect of profiled sheeting in the past decades, research on sandwich panels started only at the beginning of the 21st century with the progressive evolution of sandwich panel constructions.

Hedman-Petursson performed full-scale tests and numerical analyses in 2001 to investigate the resistance of members restrained by sandwich panels against in-plane buckling [4].

Since this effect is ignored in current design recommendations, this was the first publication in the state of art to take this effect into consideration.

In 2002 a design guide was developed by Höglund in cooperation with the Swedish Institute of Steel Construction [5], which gives several examples for shear panel constructions. An experimental test program denominated as the EASIE project [6] was conducted between 2008-13 to investigate the stiffening effect of sandwich panels in regards to the whole portal frame building, though fire scenarios were out of the scope of this investigation [7].

After overviewing international research activities the conclusion is, that even there is existing research activity according to the restraint effect of sandwich panel constructions, still, fire situations are not covered by current design recommendations [8-9].

The primary objective of this paper is the introduction of experimental test results of structural members restrained by sandwich panels at various elevated temperatures and the assessment of experimental results in regards to load-bearing capacity in the function of temperature.

Correspondence
Anita Lendvai
Budapest University of Technology and Economics
Structural Engineering Department
Müegyetem rkp. 3.
H-1111 Budapest
Email: lendvai.anita@epito.bme.hu

Affiliations
¹ PhD student, Budapest, Hungary.
² Associate Professor, Budapest, Hungary

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1.2 Research strategy and aims

International technical literature was overviewed in state of art, with the conclusion that fire scenarios in this subject have not been analysed previously, which became the innovative feature of this research. At the same time urgent need seem to rise to follow the behaviour of steel portal frames restrained by sandwich panels, thanks to different accidents caused by fire all over Europe.

As part of the above mentioned RFCS-STABFI program, experimental test series were carried out at the Department of Structural Engineering, Budapest University of Technology and Economics. The test series aimed to study the behaviour of structural members, centrally compressed HEA sections restrained by 3.0 x 3.0 m sandwich panels and trapezoidal sheeting at ambient and elevated temperatures. The stability behaviour of structural members at elevated temperature was neither tested and nor taken into consideration in current design proposals.

The principal aim of the whole project is to develop a design method, which is capable of taking into account the restrain provided by sandwich panels to structural members at elevated temperatures. This paper presents the experimental member testing in details with the corresponding results in the means of load-carrying capacity in the function of temperature and the identification and introduction of typical failure modes.

2 Test set-up

2.1 Test arrangement

The primary focus of this chapter is the introduction of experimental stability tests carried out at ambient and elevated temperatures. Fig. 1. introduces the general three-dimensional scheme of the test setup.

![Figure 1: 3D View of the Test Setup](image)

For investigating the stabilization effect of sandwich panels the core type and thickness were varied as follows: mineral wool core with 100 or 230 mm thickness, and with 0.6 mm thick outer sheet and 0.5 mm thick inner sheet type; and PIR panels with 100 or 160 mm thick core and had inner sheet thickness of 0.4 mm and outer sheet thickness of 0.5 mm. Besides sandwich panels, two types of trapezoidal sheeting were applied: with the profile height of 153 mm and 0.9 mm thickness, and 100 mm profile height with 0.88 mm thickness. The steel grade of sheeting in all cases was S280GD.

The panel to structural member fixings were 5.5 mm diameter self-drilling screws at every rib or in every 300 mm depending on the type of the panel, while shot nails were used for trapezoidal sheeting.

2.2 Test program

The test matrix of 18 tests is shown in Table 1. The following parameters were varied:

- type of structural member: hot rolled HEA120 or HEA160; cold rolled SHS250x150x6,
- cladding type: sandwich panel with PIR or mineral wool core, trapezoidal sheeting with two different heights and thicknesses,
- the temperature of inner sheet: ambient (20 °C) or elevated (200, 250 or 300 °C).
Table 1 Test matrix

| Cladding                        | Cladding thickness [mm] | Temperature [°C] |
|---------------------------------|------------------------|-----------------|
| Sandwich panel with PIR core    |                        |                 |
|                                 | 100                    | 20              |
|                                 |                        | 200             |
|                                 |                        | 250             |
| Trapezoidal sheeting (t=0.88 mm)|                        | 20              |
|                                 | 160                    | 200             |
|                                 |                        | 250             |
| Sandwich panel with mineral wool core |                  | 20              |
|                                 | 100                    | 200             |
|                                 |                        | 250             |
|                                 | 200                    | 300             |
|                                 |                        | 300             |
| Trapezoidal sheeting (t=0.9 mm) |                        | 153             |
|                                 | 200                    | 300             |

The ceramic heating pads were placed on the inner side of the cladding in two 100 cm wide zones parallel with the middle structural member. Ceramic heating pads were also placed on the flange and the web of the middle structural member in horizontal and vertical position, see Fig. 3. The surface of the specimen (i.e. above the ceramic heating pads) was insulated with mineral wool sheets.

Table 2 Temperature of cladding and structural members

| Temperature of inner side cladding | Temperature of 3 side protected HEA 120 profile |
|-----------------------------------|-----------------------------------------------|
| 20 °C                             | 20 °C                                         |
| 200 °C                            | 65 °C                                         |
| 250 °C                            | 105 °C                                        |
| 300 °C                            | 153 °C                                        |

3 Test procedure

3.1 Heating method

The fire situation was simulated by heating the top side of the cladding (i.e. the inner face of the sandwich panels or trapezoidal sheeting of an industrial building), and the loaded middle structural member by ceramic heating pads. Tests were completed at three different temperature levels (ambient and elevated): 20, 200, and 250 °C for PIR core sandwich panels and 300 °C for mineral wool core sandwich panels. As the steel structural members were considered fire protected, therefore the temperature increase $\Delta \theta_{a,t}$ of a fire-protected steel member was calculated according to EN 1993-1.2 [7], with the Eq. (1) below.

$$\Delta \theta_{a,t} = \frac{\lambda_P}{c_{p,a} V} \left( \frac{1}{1+\frac{\lambda_P}{c_{p,a} V}} \right) \left( \theta_{g,t} - \theta_{a,t} \right) \Delta t - \left( \frac{\Phi}{e^{\Phi} - 1} \right)^{1/\Phi}$$

The calculated temperatures of protected steel members are listed in Table 2 in the function of the inner side cladding temperature. The heating procedure was carried out with two Weldotherm’s Standard Europa heating machines and ceramic heating pads with the heating rate of 16.67 °C per minute.

3.2 Loading method

Force-controlled hydraulic jacks were used to apply the axial forces on the specimens. The load was increased monotonically until the failure of the specimens with the loading rate of 5 kN/sec. The tests were stopped at the failure of the specimen.

Axial compression was applied by the horizontally unrestrained column with the use of the two symmetrically placed hydraulic jacks.

The tests were completed as steady-state, which means that the temperature was kept constant by the ceramic heating pads after reaching the desired temperature level, and then the axial compression load was increased until failure.

3.3 Measured parameters

The following measurements and observations were conducted during the tests:

- temperatures of the upper flange and web of the loaded middle structural member (two thermocouples per test);
- temperatures of the cladding on the exposed and unexposed side (one thermocouple and ten temperature controllers below the ceramic heating pads per test);
- displacements of the middle structural member at midspan: one displacement in the plane of the cladding, and two out-of-plane displacements at the two edges of the upper flange;
- axial displacement at the moving support of the main structural
member;
- applied load by load cell;
- visual observation of the failure mode.

These measurements are detailed in the following.

Heating of specimen was controlled by temperature controllers of the ceramic heating pads. Ten temperature controllers were attached to the panel or trapezoidal sheeting by self-drilling screws in each specimen, and each one controlled the heating of 3–4 heating pads. The specimen temperature was recorded by coated K type thermocouples with 2 mm diameter marked as TC1, TC2, and TC3, on 3 points on the midspan of the middle structural member (see Fig. 7.). The relative deformation of a connection between the cladding and the structural member was measured by an optical extensometer. The two sensors of the extensometer were placed on the central axis of the middle structural member and on the cladding close to the connection.

Displacements were measured in 4 points with the help of displacement transducers (shown in Fig. 4.), and data was recorded on a frequency of 2 Hz: axial displacement at the support (P2), in-plane displacement of the middle structural member’s upper flange at midspan (P1H), and out-of-plane displacements of the middle member’s upper flange at midspan in two points (P1V1 and P1V2).

The applied force was also recorded by load cell to be able to determine the load-bearing capacity.

The overall behaviour and failure of the specimen were also monitored visually.

The failure mode of the restrained member was flexural buckling around the weak axis (see Fig. 5.).

Besides the above-mentioned failure modes of structural members, other failure types of the cladding were observed, detailed as follows (Fig. 6.):
- hole elongation in the sheeting at the connection between the middle structural member and cladding,
- local buckling of sheeting around screw head at middle structural member,
- screw bending,
- delamination of sheeting at elevated temperature.

During testing, the out-of-plane and in-plane displacements of middle structural members were recorded with the corresponding load values. In order to investigate the restraining effect of different cladding systems at various temperature levels the force-displacement diagrams were produced for each test, which are shown in Fig. 7–8, in which the axial load is shown in the function of the out-of-plane displacements.

The pinned connection at the beginning of the tests caused some oscillation in test results, as the tested member could not be placed precisely into the pin nest during erection. At the beginning of the tests, with the start of loading the pin sphere slipped into its final position to the pin nest, which caused the inaccuracy of results at the beginning phase of testing.
4.3 Ultimate load

During the evaluation of test results, the ultimate compressive strength of loaded members was determined, as well as the ultimate compressive strength ratios at elevated temperatures in comparison with the results at ambient temperature, which are summarized in Table 4.

The results showing that the highest ultimate force of axially loaded HEA120 members at ambient temperature is provided by the restraint of PIR sandwich panels, though at elevated temperature the decrease in ultimate force provided by PIR sandwich panels is higher than in the mineral wool panel constructions. Increasing the temperature to 200 °C decreases the ultimate force by 37-47 % in PIR cases, while 23-37 % in mineral wool panel configurations. Application of thicker panel in these specimens is not resulting in higher compressive strength neither at ambient nor at elevated temperatures. In some cases, the ultimate load at elevated temperature is slightly higher than the ambient temperature that is due to the small effect of heating within the scatter of the compressive strength.

5 Numerical analyses

5.1 FE model

A numerical study was performed in order to study the behaviour of members restrained by different size of sandwich panels. The FE model was verified and validated upon the experimental tests, and developed in Ansys Mechanical APDL 14.5 environment [10].

The core of the sandwich panels were represented by 10-node SOLID187 elements with three translation degree of freedom per node, while the upper and lower sheeting of panels and the hot-rolled HEA120 sections are modelled with by 4-node nonlinear SHELL181 elements. An initial gap was defined between the lower sheeting of the panel and the upper flange of the hot-rolled beam section, with the half-thickness of the flange (see Fig. 9).

One end of the axially loaded middle beam was restrained in all direction, while the other end's axial displacements allowed in axial direction. The end sections of the two side beams were restrained vertically (out of the sandwich panel's plane).

In order to provide the optimum mesh size, mesh sensitivity study was performed on a smaller scaled FE model, investigating the optimum mesh size for sandwich panels. The investigated case included 3000 x 1000 mm sized, 100 mm thick simply supported mineral wool panel, which was subjected to increasing out-of-plane displacements at midspan. The results on Fig. 10 showing, that 25 mm sized mesh provides optimum mesh size in the investigated case.

The mesh size of the panel is varied in the width of the specimen: around the beam the applied mesh size was 25 mm, while 40 mm and 75 mm sized mesh was generated towards the edges of the panel beam (see Fig. 11).
The screws are represented with nonlinear spring elements, i.e. upper springs (COMBIN39 elements in Ansys) were defined between the upper and lower sheet of panels, and lower springs between the lower sheet and the upper flange of the beam (see Fig. 1).

Contact areas are defined between the upper flange of the beam and the lower sheet of the sandwich panels (denoted as CONTA173 and TARGE170 in Ansys). For material model multilinear isotropic hardening material model was applied. The material properties of hot-rolled section and sheetings was measured in laboratory tests, so these data were used in numerical analyses. For hot-rolled sections the yield strength of 445 N/mm$^2$ was applied, and the elastic modulus in this case was 258 GPa. The material properties for different sheetings are summarized in Table 3.

Axial load was applied at the end section of the middle beam, and corresponding axial displacements were calculated (see Fig. 2).

Heating was simulated by decreasing the spring stiffnesses of the lower springs (between the upper flange of the beam and the sheeting), and with the decrease of yield strength of lower steel sheeting, and the hot-rolled beam.

The failure mode of the FE model is introduced in Fig. 3, which shows a good agreement with failure modes of the experimental tests.

Table 3 Material properties

| Cladding                | Cladding thickness [mm] | Sheet thickness | $f_y$ [N/mm$^2$] | $E$ [GPa] |
|-------------------------|-------------------------|-----------------|-----------------|----------|
| Sandwich panel with PIR core | 100                     | upper           | 305             | 188      |
|                         |                         | lower           | 323             | 179      |
|                         | 160                     | upper           | 382             | 265      |
|                         |                         | lower           | 256             | 202      |
| Sandwich panel with mineral wool core | 100                     | upper           | 406             | 251      |
|                         |                         | lower           | 318             | 204      |
|                         | 230                     | upper           | 400             | 258      |
|                         |                         | lower           | 381             | 271      |

Figure 11 Nonlinear springs applied in 10 rows

Figure 12 Axial load applied at the end section

Figure 13 FE model – failure mode of specimen
The results of the comparison between the validated numerical model and the experimental results are shown in Fig. 14-17.

![Figure 14 Comparison of results of experimental tests and numerical study – 100 mm thick mineral wool panels](image1)

![Figure 15 Comparison of results of experimental tests and numerical study – 230 mm thick mineral wool panels](image2)

![Figure 16 Comparison of results of experimental tests and numerical study – 100 mm thick PIR panels](image3)

![Figure 17 Comparison of results of experimental tests and numerical study – 160 mm thick PIR panels](image4)

Table 4 indicates the comparison of the ultimate load values between FE model and experimental results. A better fit can be seen on the FE model of the specimens with mineral wool core, where the difference is between 1-20 %. In the case of PIR paneled cases a larger difference of 1-41 % can be detected. The reason of the larger difference in PIR cases might be, that the delamination of the panel started at earlier temperature level in the experimental tests – at about 200 °C - , than in the mineral wool cases, which effect was not simulated in the numerical model. For this reason in PIR cases large initial displacements were experienced during testing at elevated temperature, while the numerical model resulted larger initial stiffness.

In mineral wool cases at ambient temperature the comparison of numerical and experimental force-displacement diagram shows a better fit, than in PIR cases, in the means of displacements and load bearing capacity as well. The ultimate load of these specimens at elevated temperature levels is in the range of 1-20 % compared to the experimental results. The results showing, that the thicker sandwich panel provides stiffer restraint at elevated temperature, than the 100 mm thick sandwich panel.

The developed numerical model is capable to follow the behavior of the introduced experimental tests, in the means of ultimate load and failure modes. Further steps of research will be a parametric study to widen the domain of investigated cases with noninvestigated section sizes, and to derive data for design method for stabilization of cladding by sandwich panels at elevated temperature level, which is the innovative feature of the presented RFCS-STABFI research.

| Cladding Material | Cladding Thickness (mm) | Temperature (°C) | Ultimate Load (kN) – Experimental Test | Ultimate Load (kN) – FE Model | Comparison [%] |
|-------------------|-------------------------|------------------|----------------------------------------|----------------------------|----------------|
| Sandwich panel with PIR core | 100 | 20 | 1060 | 1068 | 99 |
| Sandwich panel with PIR core | 200 | 673 | 961 | 69 |
| Sandwich panel with PIR core | 250 | 652 | 912 | 71 |
| Sandwich panel with mineral wool core | 100 | 20 | 1001 | 1072 | 93 |
| Sandwich panel with mineral wool core | 160 | 200 | 530 | 896 | 59 |
| Sandwich panel with mineral wool core | 250 | 655 | 878 | 75 |
| Sandwich panel with PIR core | 100 | 200 | 762 | 760 | 100 |
| Sandwich panel with PIR core | 300 | 754 | 627 | 120 |
| Sandwich panel with mineral wool core | 230 | 20 | 1057 | 1073 | 99 |
| Sandwich panel with mineral wool core | 230 | 200 | 663 | 773 | 86 |
| Sandwich panel with mineral wool core | 300 | 763 | 757 | 101 |
6 Conclusions

This paper introduces the results of experimental tests of structural members restrained by sandwich panels and trapezoidal sheeting carried out in the so-called STABFI project within the frame of "Research Fund for Coal and Steel" program financially supported by the EU. The innovative feature of this research is the investigation of the restraining effect of various cladding systems to the primary structure at elevated temperature, which is not taken into consideration by the current regulations. In total 54 tests were carried out at ambient and elevated temperatures at the Department of Structural Engineering of the Budapest University of Technology and Economics, from which the results of 18 tests were introduced, including HEA120 structural members by sandwich panels or trapezoidal sheeting.

On the applied structural member different types of sandwich panels or trapezoidal sheeting were installed, i.e. mineral wool panels with the thickness of 100 mm and 230 mm, and panels with PIR core with the thickness of 100 mm and 160 mm. Furthermore, 100 mm and 153 mm profile height trapezoidal sheeting were also applied.

The overall dimensions of the test specimens were 3.0 m x 3.0 m sized diaphragms, where the spacing of the three, hot-rolled beams was 1.5 m. The claddings were installed on the lower face of the structural members. The simply-supported main member with a span of 3 m is located at the middle of the cladding, and it was subjected to axial compression load. Self-drilling stainless steel screws were used to connect the cladding to the structural members. The specimens were tested at various inner steel sheet temperatures of 20, 200, 250, 300 °C.

After reaching the required temperature level, a monotonically increasing load was applied to the specimen’s middle member

The conclusion of the experimental tests is to acquire data regarding the decrease in the stabilizing effect in the function of increasing temperature simulating fire.

The developed numerical model shows good agreement with the experimental results. It can be stated, that the developed numerical model is capable to predict the ultimate compressive load of investigated members, and is a sufficient tool for investigation of structural members restrained by sandwich panels at elevated temperature levels. In further steps of research parametric study will be followed, and a design method will be presented in regards of stabilization of structural members by sandwich panels at elevated temperature levels.

Further aim of the research is that based on an extended numerical research program a proposal can be formulated in order to take into consideration the stabilizing effect of claddings in regards to the primary structural members, which is out-of-scope of the current standards.

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