Influence of type and orientation of thin-walled beams on the interaction effectiveness with sandwich panels

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ABSTRACT: In the paper, the problem of the interaction between thin-walled beams with sandwich panels has been presented. The sandwich panels consist of steel external facings and the polyurethane foam core. The Z and C cross-section shapes and their various mutual orientations have been considered. The stabilization effect provided by the sandwich panels was investigated in a full-scale laboratory experiment and then compared with the numerical model. The full-scale test allowed for validation of the numerical model created in the Abaqus/CEA environment. The Newton-Raphson procedure with geometrical and material nonlinearity was implemented in order to perform the numerical computations.

1 MOTIVATION

In recent times, thin-walled beams are more and more frequently used as elements of a steel hall system (purlins, wall beams, construction of casings and eaves beams). The main advantage of designing structures with thin-walled elements is a favorable mass to bearing capacity ratio and mass to stiffness ratio. On the other hand, structures with thin-walled elements also have a negative effect due to the large slenderness of its walls – thin-walled cross sections are susceptible to the local loss of stability. Both local loss of stability (local buckling) as well as distortional buckling and global buckling (flexural, torsional, lateral-torsional and flexural-lateral) are the most common forms of the thin-walled beams instabilities.

The interaction between structural elements is an important topic. In this case, structural elements which are understood as a roof or a wall sheathing are interacting with a steel supporting framework. Trapezoidal sheets and sandwich panels are commonly used as a roof or wall sheathing in steel structures. These types of sheathings are characterized by a high bending stiffness (plate behavior) and a high shear stiffness (diaphragm behavior). Therefore they can provide lateral and torsional buckling restraint of steel elements. Taking into account the mechanical interaction between a steel supporting framework and an external sheathing provide possibility for computing the construction as three-dimensional plate-diaphragm-rod load-bearing structures. For example Lucas et al. 1997a, b introduced simplified model and a full model which defines the interaction between thin walled beams and the sandwich panels. The procedure which is capable of determination the value of critical buckling moment of the thin-walled beam restrained by trapezoidal sheeting was proposed by Ye et al. 2002, Li 2004 & Chu et al. 2004. It is worth to mention that taking into the consideration the described influence may result in the global weight of a structure reduction and consequently, lowering the total cost.

The subject matter of steel elements interacting with trapezoidal sheets is widely discussed in the literature and has been reflected in EN 1993-1-3 code guidelines. In recent years, sandwich panels are more often used as elements of hall casing because of their good mechanical and thermal properties. The increasing popularity in using this type of sheathing has

prompted researchers to also analyze the interaction of steel construction and sandwich panels, which recently were not used in common for the stiffening the structural elements. Over the last decade, there have been carried out some laboratory and numerical researches by Dürr 2008, Dürr & Misiek 2011 which confirm that not only the trapezoidal sheets but also sandwich panels can provide the lateral restraint of the thin-walled elements. This topic was also discussed in research projects, which resulted in developing methods defining the interaction between sandwich panels and thin-walled beams. Furthermore, these methods have been also included in the European recommendations.

2 PROBLEM FORMULATION

The analysis was carried out on cold-formed sections which were made of 1.5 mm thick and 220 mm width sheet metal with the total length equal to 3300 mm. Two shapes of cross-sections were formed from steel sheets: “Z” and “C” with dimensions given in Figure 1.

So far, the analyses of the interaction between thin-walled beams and sandwich panels have been conducted for classical orientation of the thin-walled elements, see ZZ-1 and CC-1 models depicted in Figure 2. In this paper, authors had decided to analyze different orientations of thin-walled beams. The aim of this research was the analysis of the influence of thin-walled beams orientation stabilized by the sandwich panels on the thin-walled element buckling form. Nine different beam orientations have been analyzed: three of the Z-beams (Figure 2a), three of the C-beams (Figure 2b) and three with mixed composition of C- and Z- beams (Figure 2c).

Figure 1. The dimensions of analyzed cross-sections, where S and G is location of the shear center and center of gravity, respectively.

Figure 2. The relative orientation of the thin-walled elements – description in main text.

Figure 3. Scheme of the laboratory test-bed (Ciesielczyk & Studziński, 2017).

3 LABORATORY BACKGROUND

Laboratory experiments cover full-scale experiments and material tests. Two thin-walled beams with the length equal to 3300 mm were stiffened by two sandwich panels with the width equal to 1100 mm. The sandwich panel core of a thickness 100 mm was made of polyurethane foam. The scheme of the laboratory test-bed is presented in Figure 3. Two beam cross-sections were taken under consideration: Z-beam and C-beam with dimensions given in Figure 1. Four angle cleats of a length 0.1 m were used in order to avoid the local compression of the thin-walled beam at the supports. During experimental tests two beam arrangements were investigated: ZZ-1 model (Ciesielczyk & Studziński, 2017) and CC-1 model (Studziński & Ciesielczyk, 2016). The sandwich panels which were used in the experiment consisted of two zinc-coated steel facings and thick and soft polyurethane core. The following geometrical dimensions of sandwich panel layers were measured: thickness of the core $d_c=80$ mm, thickness of the external $t_{Fe}=0.594$ mm and internal facings $t_{Fi}=0.490$ mm. The aspect of the connection stiffness was considered in other paper (Studziński & Ciesielczyk, 2019).

In order to determine the material properties, such as: Young's modulus, yield strength, ultimate tensile strength and stress-strain characteristic, the tensile tests have been carried out for the material samples of sandwich panel facings (12 samples) and thin-walled beams (6 samples). A tensile specimens had a shape of standardized cross-section sample and consisted of two shoulders and a gage between them. The dimensions of the prepared samples are presented in Figure 4a. Conducted tensile tests indicated that Young's modulus for the steel facing material and for the steel thin-walled beam material is equal to 190 GPa and 198 GPa

Figure 4. Tensile test: a) the steel sample dimensions, b) the stress-strain curve for steel from beam.

respectively. The value of the Poisson's ratio for steel is equal to 0.3. On the basis of the performed tests, the steel which was considered as element's materials was defined as mild steel with a plasticity effect (significant increase of strain without stress increase). The stress-strain curves obtained from the experiment for thin-walled beam steel (6 samples) are presented in Figure 4b. The average value of the upper yield strength determined by the experiment is equal to 348.87 MPa while the value of ultimate tensile strength equals 402.72 MPa.

4 LABORATORY BACKGROUND

The numerical output model had been defined within the Abaqus/CEA environment (the model was also presented in Ciesielczyk & Studziński, 2017). The numerical model had been verified and validated by the laboratory experiments described in the above subsection. The created numerical model reflected the laboratory experiment thus it consists of angle cleats, thin-walled beams with various shapes and orientations, sandwich panels, and an I-beam.

Figure 5. Scheme of the numerical model.

All steel properties used in the numerical model were determined by the laboratory experiments. The true stress-strain curve implemented into the numerical model has been presented in Figure 4b by the continuous line. The true stress and strain were determined by the following formulas:

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

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

$$\varepsilon_{true}^{pl} = (\varepsilon_{true} - \sigma_{true})/E, \quad (3)$$

where: σ_{true} represents true stress, σ_{nom} represents nominal stress (engineering), ε_{nom} represents nominal strain (engineering), ε_{true} represents true strain, and ε_{true}^{pl} represents plastic true strain (required by Abaqus).

The properties of the sandwich panel core material such as: the shear modulus ($G_c=3.2$ MPa) and the Poisson ratio ($\nu_c=0.05$) have been adopted from the previous work (Studziński, 2019). The non-linear stress-strain characteristic was used in the numerical model. The load in the numerical model consisted of: component's own weight and the concentrated force traversed into an uniformly distributed load by the I-beam. The boundary conditions have been applied to angle cleats in order to reflect the real connection with the support structure. Furthermore, in order to reduce the computation time the symmetry boundary conditions have been applied (the numerical model has been twice reduced). In order to obtain the nonlinear

Table 1. Dimensions and type of the finite elements.

Model component	FE type	FE size in [mm]	number of FE
IPE	C3D8R	10x10x10	5 940
External facing	S4R	40x40	1 998
Core	C3D8R	40x40x40	4 050
Internal facing	S4R	5x5	33 110
Thin-walled beam	S4R	5x5	14 190
Angle cleat	S4R	5x5	680

static response, the Newton-Raphson procedure with Full Newton solution technique was adopted. All components of the model have been modeled by shell and solid finite elements. Their dimensions and types are presented in the Table 1, where according to the Abaqus documentation C3D8R is a 8-node linear brick finite element with reduced integration and hourglass control while S4R is a 4-node doubly curved thin or thick shell finite element with reduced integration, hourglass control, and finite membrane strains.

5 DISCUSSION OF THE RESULTS

From the assumed nine different beam orientations the following groups can be distinguished: the thin-walled beams with the upper flange directed in the same direction (ZZ-1, CC-1, CZ-2), the thin-walled beams with the upper flange directed “outside” (ZZ-2, CC-2, CZ-3), and the thin-walled beams with the upper flange directed “inside” (ZZ-3, CC-3, ZC-1). The C and Z cross-sections have the same surface area and therefore the same self-weight per unit length, nevertheless the important differences between considered cross-sections refer to the geometrical characteristics influencing the size of the elastic critical bending moment, see Table 2.

According to data presented in Table 2, it can be noticed that the Z cross-section is characterized by higher warping properties than the C cross-section. The higher warping properties (I_t , I_z , I_ω), the higher magnitude of the elastic critical moment for lateral torsional buckling can be provided by the cross-section. Additionally, the position of the applied transverse load with regard to the shear center is significantly closer for Z than C cross-section. Therefore this parameter – which represent the point at the cross-section where the application of load does not cause its twisting – is favorable for Z cross-section. In other words, the torsional stresses, from the load of the same magnitude and way of application, are smaller for Z than C cross-section. On the other hand, principal central axes of both considered cross-sections do not coincide with the loading plane. This leads to biaxial bending nevertheless, in the case of C cross-section, the inclination angle of the principal central axes (from the loading plane) is 20 times smaller compared with Z cross-section. It means that the biaxial bending moment decomposition produces a larger bending moment against the weaker axis in the case of Z cross-section than in the case of C cross-section.

Table 2. Selected geometrical characteristic.

No.	Geometrical characteristic	Z-section	C-section	Difference
1.	I_t – torsion constant	0.02 cm ⁴	0.02 cm ⁴	0.0 %
2.	I_z – second moment of area about the weak axis	14.89 cm ⁴	8.61 cm ⁴	42.2 %
3.	I_ω – warping constant	259.00 cm ⁶	209.00 cm ⁶	19.3 %
4.	α_0 – inclination angle of the principal axes	24.90°	2.50°	90.0 %
5.	y_s – distance of the shear center from the web	2.41 mm	–21.39 mm	987.6 %

Figure 6. Load-displacement paths of the middle point of a bottom flange of the thin-walled beam.

Figure 7. Maps of displacements for selected models – the cross section in the middle of the sandwich panel.

The resultant load-displacement paths of the middle point of the bottom flange of the left thin-walled beams is presented in Figure 6. The results of the ZZ-2 and ZZ-3 are not included due to the lack of convergence of the nonlinear FEA analysis. The deformation maps of three selected models are presented in Figure 7.

6 CONCLUSIONS

The following conclusion can be formulated. Firstly it was observed that the Z cross-sections are sensitive to the biaxial bending while the C cross-sections to twisting which leads to an initial greater stiffness of the system with C-beams than in the case of the system with Z-beams. This is due to:

- the initial in-plane bending of the C-beams because of small inclination angle of the principal axes with respect to the load plane, and
- the initial biaxial bending of the Z-beams because of large inclination angle of the principal axes with respect to the load plane.

Secondly the further increase of the loading (above “initial” i.e. in our cases above 1 kN) leads to:

- significant stiffness reduction of C-beams due to twisting (large distance between loading plane and the shear center), and
- gradual decrease of flexural stiffness of Z-beams (small distance between loading plane and the shear center).

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