JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
51, 2, pp. 497-504, Warsaw 2013

EXPERIMENTAL AND NUMERICAL (FSM) INVESTIGATIONS OF THIN-WALLED BEAMS WITH DOUBLE-BOX FLANGES

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In the paper, experimental and numerical investigations of thin-walled beams with double-box flanges were presented. They were a continuation of researches conducted at the Unit of Strength of Materials and Structures at Poznan University of Technology. Numerical results obtained with the Finite Strip Method (FSM) were compared with experimental ones and used for validation of analytical solutions.

Key words: thin-walled beams, FSM, experimental investigations

1. Introduction

In the paper, results of numerical analyses and experimental investigations of cold-formed, thin-walled beams with double-box flanges were presented. The beams were loaded with a bending moment. Software CUSFM ver. 3.12 of Prof. B. Schafer (http://www.ce.jhu.edu/bschafer/cufsm/; Schafer and Ádány, 2006), based on the Finite Strip Method, was used for numerical simulations. The obtained results were compared with the findings of experimental studies.

The buckling of thin-walled beams, with clear distinction between buckling of web and flanges, was described in this paper. Thin-walled beams tend to buckle under bending. Therefore, it is justified to look for new shapes of cross-sections that would increase the strength and stability of beams.

Researches on thin-walled structures have been conducted for many years. Some of them have focused on experimental investigations, others on analytical models. Contemporary structural materials make it possible to reduce the weight of structures with a simultaneous increase in their strength and stability. Thin-walled beams tend to buckle locally due to the high wall thickness-to-depth ratio. Similar studies were done by Pastor and Roure (2008), Camotim and Dinis (2009), who investigated thin-walled beams loaded with bending moments, concentrated forcers or distributed loads. They presented formulas for critical loads and equations describing the interaction between local and global buckling.

The load capacity of cold-formed thin-walled beams is usually restricted by their stability and post-buckling behaviour. Their strength was considered by Cheng and Schafer (2007) and Trahair (2009). Experimental investigations, stress and displacement distribution of cold-formed beams were shown by Paczos and Magnucki (2009). Other examples of papers directly connected with the subject of this work are Biegus and Czepiżak (2008), Magnucki and Paczos (2009), Magnucki *et al.* (2010), Paczos and Wasilewicz (2009) or Mahendran and Jeyaragan (2008).

The paper concerns thin-walled beams with double-box flanges made of a cold-rolled steel sheet (Fig. 1). This is a part of broader research on thin-walled beams and search for new shapes of cross-sections that would increase the strength and stability of beams. They have been conducted for a few years at the Unit of Strength of Materials and Structures at Poznan University of Technology.

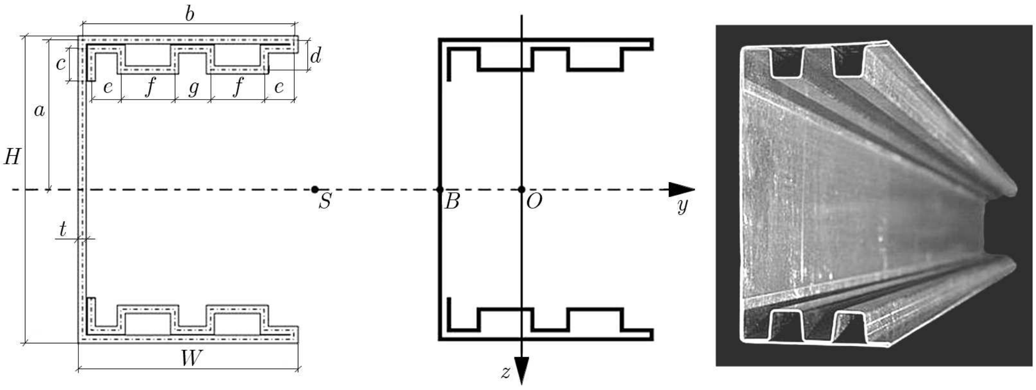

Fig. 1. The cross-section of the investigated beams

2. Description of the investigated cross-sections

All the investigated beams were cold formed and made of steel sheets of known material properties. Their cross-section was the same but their wall thickness varied. The beams were manufactured by Polish company "Pruszyński Sp. z o.o.", Sokolow, Poland.

2.1. Geometrical properties

The dimensions of the cross-section of the investigated beams were following (Fig. 1): beam depth $H = 160\,\mathrm{mm}$, flange width $b = 0\,\mathrm{mm}$, wall thickness $t = 1.00\,\mathrm{mm}$ and $t = 1.25\,\mathrm{mm}$, $c = 23\,\mathrm{mm}$, $d = 18\,\mathrm{mm}$, $e = 14\,\mathrm{mm}$, $f = 17\,\mathrm{mm}$, $g = 15\,\mathrm{mm}$. The presented double-box flanges improved the strength and stability of beams and decreased their weight.

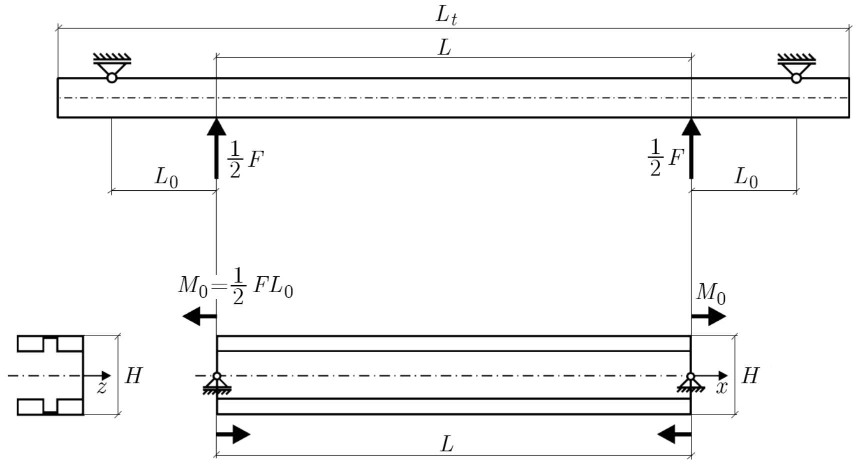

Fig. 2. Longitudinal dimensions of beams and a loading diagram

The longitudinal dimensions of beams and a loading diagram are presented in Fig. 2. The marked dimensions were following:

- total length $L_t = 2000\,\mathrm{mm}$,
- distance between concentrated forces $L = 500\,\mathrm{mm}$,
- distance between the concentrated force and the support $L_0 = 730\,\mathrm{mm}$.

The tensile force of the testing machine was divided into two equal concentrated forces. The beams were supported (fixed) at two places. This system of forces and supports resulted in a constant bending moment at the centre segment of beams.

2.2. Material properties

The investigated beams were made of steel sheets. Their material properties were following: Young's modulus $E = 181\,\text{GPa}$, Poisson's ratio $\nu = 0.3$ and yield strength $\sigma_{eH} = 329\,\text{MPa}$. They were determined by testing 5 samples prepared according to Eurocode 3.

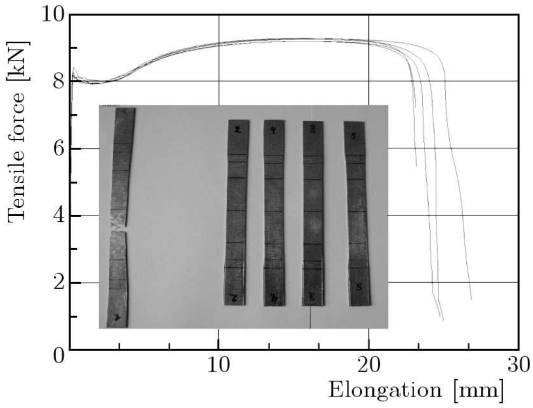

Fig. 3. The stress-strain curve of specimens – steel DX51

The results of tensile tests were presented in Fig. 3. The specimens were made of steel DX51, hot-dip galvanized, zinc coating $200\,\text{g/m}^2$. These findings made it possible to determine material properties that were used in numerical analyses and analytical models.

3. Numerical analysis – FSM

In order to better understand the buckling of the investigated beams, numerical analyses were done. Moreover, the obtained results were compared with the experimental ones. The beams were analysed using FSM (Finite Strip Method). In recent years, there have been a few significant works devoted to this method. For example, Adany and Schafer (2006a) presented a method for calculating critical forces of thin-walled beams based on FSM. They used GBT for decomposition of different buckling modes. Their new method was called cFSM (constrained FSM). Its application and some examples were presented by Adany and Schafer (2006b). Adany *et al.* (2010) demonstrated the computer program CUFSM for determination of buckling modes based on cFSM. Djafour *et al.* (2010) proposed a procedure for calculation of the constrain matrix in cFSM for global and distorsional buckling modes. It can be used for analysis of closed-section beams.

The beams were modelled with 36 elements (37 nodes). They were loaded by a bending moment constant along the whole beam, in such a way that the obtained load factors were equal to actual critical stresses divided by 100. The discretization error and the convergence of results were checked by doubling and quadrupling the number of elements. Simply supported beams were analysed since this kind of support was considered during experimental investigations.

The buckling modes and load factors are presented in Figs. 4 and 5. They were equal to:

- 1.41 for the beam of wall-thickness $t = 1.00\,\text{mm}$,
- 2.20 for the beam of wall-thickness $t = 1.25\,\text{mm}$.

The critical stresses for the determined buckling load factors were equal to $\sigma_{cr} = 141\,\text{MPa}$ and $\sigma_{cr} = 220\,\text{MPa}$, respectively.

The buckling modes presented in Fig. 6 referred to local buckling in an elastic range (stresses were below the yield strength). In both cases, there was an interaction between the compressed flange and web of the beam. The buckling modes were similar, but in the beam of the wall thickness 1.00 mm, the flange buckled outwards and the web inwards. In the beam of the wall thickness 1.25 mm, the flange and web moved in the opposite direction.

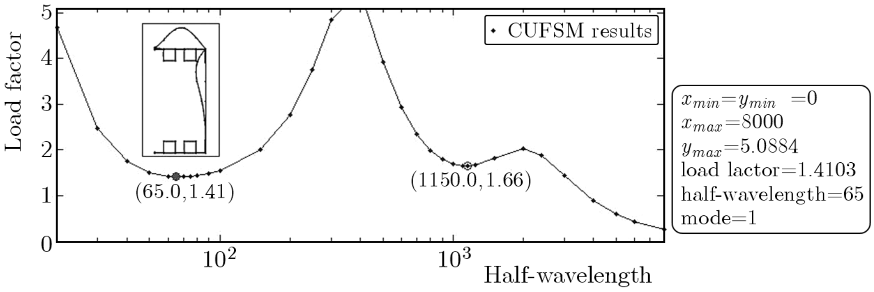

Fig. 4. FSM – critical forces vs. half-wave length, a beam with double-box flanges, wall thickness $t = 1$ mm

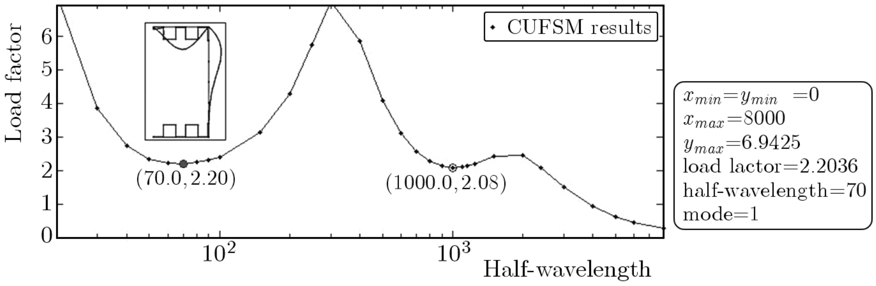

Fig. 5. FSM – critical forces vs. half-wave length, a beam with double box-flanges, wall thickness $t = 1.25$ mm

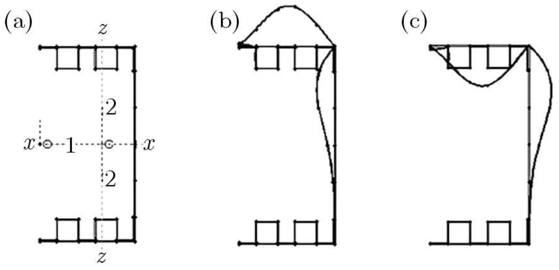

Fig. 6. FSM – buckling modes of the beam, wall thickness is equal to (b) $t = 1$ mm and (c) $t = 1.25$ mm

4. Experimental investigations

The experimental investigations were done at the Laboratory of Strength of Materials and Structures, Institute of Applied Mechanics at Poznan University of Technology, Poland. Ten beams of the wall-thickness 1.00 mm and 1.25 mm and length $L = 400$, 500, 600 mm were tested. Differences between the results obtained for the beams of the same dimensions were not big. Therefore, the results were averaged and presented in tables and drawings. The principal moments of inertia (Fig. 1) were equal to: $I_y = 3030108\,\mathrm{mm}^4$ (beams of the wall thickness $t = 1.00$ mm) and $I_y = 3787635\,\mathrm{mm}^4$ (beams of the wall thickness $t = 1.25$ mm).

The following equations were used for expressing the relationship between the tensile force, bending moment and maximum stresses

$$F = \frac{2Mb_{cr}}{L_0} \qquad \sigma_{dos} = \frac{Mb_{cr}}{W_y} \tag{4.1}$$

where: Mb_{cr} – critical bending moment, L_0 – distance between the concentrated force and the support (Fig. 2), F – critical force, W_y – section modulus.

All the tests were conducted on a tensile testing machine ZWICK Z100 with mechanical drive and a custom test stand for channel beams (Fig. 7). At the web and compressed flange, there were placed four foil strain gauges. The deflection of the beams was measured with 3 beam deflection sensors WI10 (Fig.8).

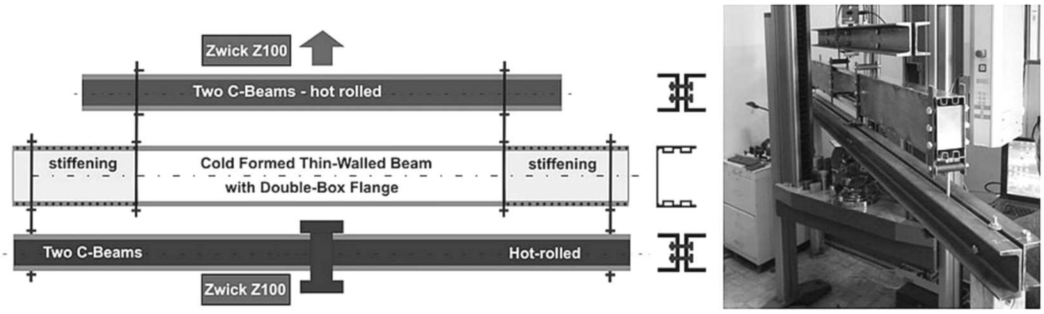

Fig. 7. Test stand: diagram and picture

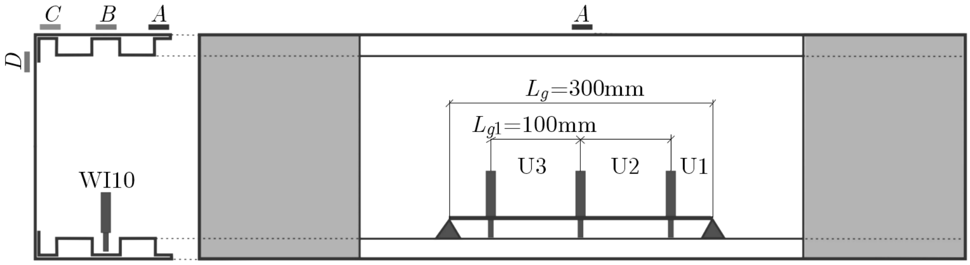

Fig. 8. Position of strain gauges and beam deflection sensors

In Fig 9, there is a graph showing the relationship between the tensile force and deflection of beams made of steel (DX51) sheets with thickness 1.00 mm and 1.25 mm. The characteristic points on the graph, were this relationship stopped to be linear, meant that at that load, the beams buckled locally. The first of points was considered as the critical load because then the cross-section of the beam got deformed. However, sometimes this deformation was not visible clearly. This assumption was confirmed and validated by FSM.

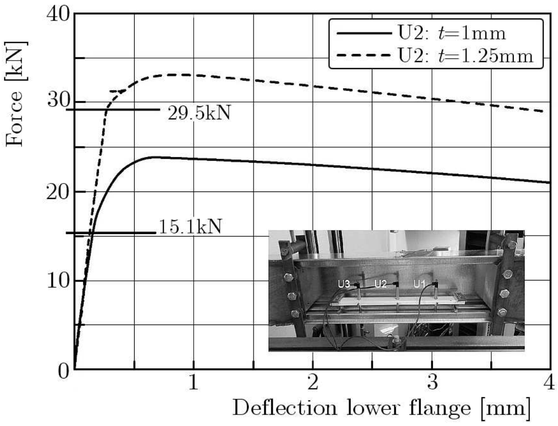

Fig. 9. Tensile force vs. deflection

During experiments, an interaction between the buckling of the web and compressed flange was observed. The graphs presented in Fig. 9 referred to the whole experiment until the moment when the investigated beams collapsed. A *slight* increase of the wall thickness by 0.25 mm almost doubled the value of critical forces.

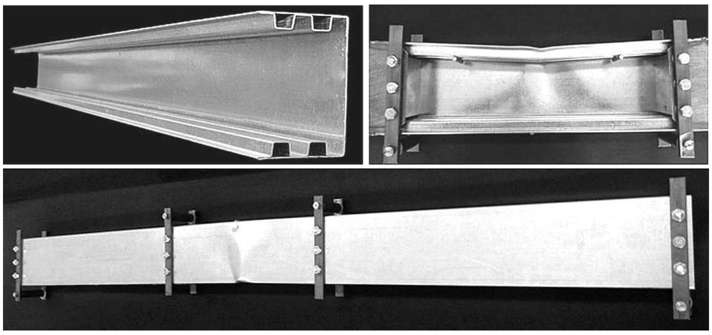

Fig. 10. The beam before and after tests

Thin-walled members usually collapse as a result of the plastic mechanism of damage (Fig. 10). If a beam is loaded with a monotonically increasing load, its behaviour can be divided into four stages: pre-buckling, non-linear behaviour, post-buckling (elastic-plastic range) and damage. Local buckling usually appears simultaneously with global one, and is a cause of low limit load which depends on a few factors: overall dimensions of the structural member, boundary conditions, kind of load and shape of the cross-section of the beam. The investigated beams buckled also quite quickly, and in most cases this was a local buckling mode (Figs. 6, 10).

5. Conclusions

The obtained results prove that it is useful to do numerical analyses, e.g. based on FSM or FEM. They help to validate and properly interpret results of experimental investigations because, in some cases, it may be difficult to determine the critical load. The initial deformation of the cross-section of a beam (buckling) may be hard to notice in the right moment because it is small.

In Table 1, the results of experimental investigation and numerical analyses are gathered. The presented critical stresses referred to the determined critical loads 15 kN and 30 kN for beams of the wall thickness, respectively, 1.00 mm and 1.25 mm.

Table 1. Comparison between the results of experimental investigation and numerical analyses (FSM)

Kind of research	Wall thickness	
	$t = 1.00$ mm	$t = 1.25$ mm
Experimental investigations – stresses [MPa]	146	225
Numerical analysis (FSM) – stresses [MPa]	141	220
Difference [%]	3.5	3.2

Numerical simulations make it possible to analyse the buckling of flanges, web and the interaction between different buckling modes. They help to build proper analytical models, e.g. by giving indications of some buckling modes.

The obtained results led to the following conclusions:

- the results of numerical analyses were in agreement with the outcome of experimental investigations, the differences between stresses were below 4%, buckling modes were the same as well,

- further increase of load, after buckling, caused not only bigger deformation of the cross-sections but also resulted in other buckling modes,
- the results justify searching for new shapes of cross-section of cold-formed thin-walled beams that have not been included in standards.

The comparison of experimental investigations with numerical analyses based on the Finite Strip Method and CuFSM software by prof. Shafer (http://www.ce.jhu.edu/bschafer/cufsm/) was presented in this paper. Numerical analyses based on the Finite Element Method were done as well, and their results were shown at Nordic Steel Construction Conference in 2012 (Paczos *et al.*, 2012).

The weight of the beam of the wall thickness $t = 1.00$ mm was equal to 9.52 kg, whereas the beam of the wall thickness $t = 1.25$ mm weighed 11.78 kg. The critical forces of those beams were equal to 14.4 kN and 27.9 kN, respectively. This means that with a relatively small increase of weight (23.7%), their strength rose by 93.7%. A similar phenomenon was observed during experimental investigations of classic cold-formed channels with a reinforced web. The critical forces of those channels were equal to 1.4 kN and 2.8 kN for beams of the wall-thickness $t = 1.00$ mm (7.92 kg) and $t = 1.25$ mm (9.92 kg), respectively, i.e. the 25% increase in the weight of the beam doubled their strength. However, in the case of channels with boxed flanges 20%, heavier beams had 10 times bigger strength (increase from 1.4 kN to 14.4 kN).

This work presents preliminary investigations done in order to better understand a problem and search for new, untypical shapes of the cross-sections of cold-formed thin-walled beams that could increase their strength and stability.

Acknowledgement

This paper was supported by Polish Ministry of Science and Higher Education, grant no. 2073/B/T02/2010/39.

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Badania doświadczalne i numeryczne (FSM) belek cienkościennych z półkami skrzynkowymi

Streszczenie

W pracy przedstawiono badania doświadczalne i numeryczne belek cienkościennych z półkami skrzynkowymi. Zagadnienie to jest kontynuacją badań przeprowadzonych w Zakładzie Wytrzymałosci Materiałów i Konstrukcji Politechniki Poznańskiej. Wyniki numeryczne otrzymane z wykorzystaniem metody pasm skończonych porównano z wynikami uzuskanymi z eksperymentu, a nastepnie użyto do weryfikacji rozwiązań analitycznych.

Manuscript received January 27, 2012; accepted for print December 20, 2012