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Research paper

Numerical investigation of steel-timber composite beams with cold-formed omega girders. Part 2: Beams with modifications and reinforced beams

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Abstract: This paper is part 2 of a numerical investigation of steel-timber composite beams with cold-formed omega girders and laminated veneer lumber slabs. After conducting a preliminary analysis of the composite beam cross-section in part 1 of the paper, a modification to the cross-section and a reinforcing method were proposed in part 2. In order to increase the load-bearing capacity of the beam, modifications, such as placing a metal sheet inside of the girder or placing a channel outside of the girder, were proposed. These modifications can be made at the production stage of the steel girders. The modification in form of a channel placed outside the omega girder provided the highest increase in the load-bearing capacity. However, the mass of the modified beam with the channel was 29.6% greater than the mass of the reference beam, and the modifying the girder using channels poses a particular challenge. For this reason, the modifications in the form of a flat sheet can be used instead of the channel. The sheet metal may be located inside the omega section to increase the aesthetics of the beam. Furthermore, the effectiveness of the carbon fibre reinforced polymer tape was analysed as a method of beam reinforcement at the building operation stage. The use of the tape resulted in increased load-bearing capacity. However, the increase in the load-bearing capacity of the beam may be limited because of the yielding of the support zone.

Keywords: carbon fibre reinforced polymer (CFRP), laminated veneer lumber (LVL), omega cross-sections, steel-timber composite beams

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1. Introduction

A numerical study of steel-timber composite beams with cold-formed omega girders and laminated veneer lumber slabs (without modifications or reinforcement) was presented in part 1 of the paper [1]. In part 2 of the paper, a modification to the cross-section as well as a reinforcing method were proposed. Placing a metal sheet inside or outside of the steel girder, and placing a channel inside or outside of the steel girder was analysed as modifications. The modifications can be made at the production stage of the girders. The carbon fibre reinforced polymer (CFRP) tape was analysed as a method of beam reinforcement at the building operation stage. The purpose of this research work was to evaluate the resistance to bending of modified composite beams.

2. Materials and methods

The reference beam consisted of an LVL slab and an omega-shaped steel girder was analysed in part 1 of the paper [1]. After investigating the resistance to bending of the reference beam, it was modified by joining the steel girder with an additional steel sheet (flat or cold-formed channel) to increase the resistance to bending. Furthermore, the reference beam was also strengthened using carbon fibre reinforced polymer tape. The modification of the cross-section can be made at the production stage of the omega-shaped steel girders. The strengthening with the carbon fibre reinforced polymer tape may be applied at the building operation stage.

2.1. The steel-timber composite beam with the modified omega girder

The cross-section of the reference beam was modified by joining the lower flange of the steel girder with an additional steel sheet. The length of the additional metal sheet was the same as the length of the steel girder.

Four types of modification were considered: type A with the metal sheet placed inside of the omega component, type B with the metal sheet placed outside of the omega component, type C with the channel placed outside of the omega component and type D with the channel placed inside of the omega component. In types A and B, the metal sheets of different thickness and width were considered. In types C and D, the cold-formed channels of different thickness were analysed. The summary of the analysed variants is presented in Table 1.

The meaning of the used symbols is presented in Fig. 1.

Table 1. A summary of the modifications of the girder

Dimension	Girder types											
	A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**C1**	**C2**	**C3**
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**D1**	**D2**	**D3**
w, mm	40	40	40	50	50	50	60	60	60	–	–	–
s, mm	–	–	–	–	–	–	–	–	–	30	30	30
t, mm	1	2	3	1	2	3	1	2	3	1	2	3

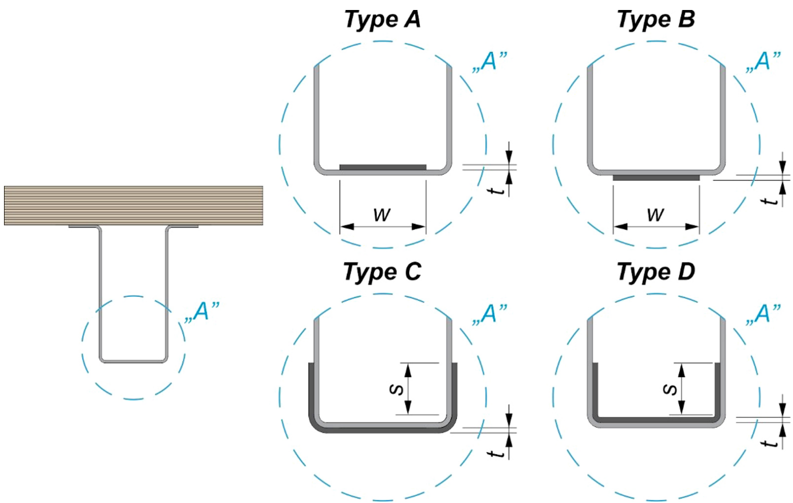

Fig. 1. The cross-sections of the modified steel-timber composite beams

The adopted height of the C-shaped reinforcement used in C- and D-beams is constant and it is equal to s = 30 mm. This is the minimum dimension which allows for the bending of the metal sheet.

2.2. The steel-timber composite beam strengthened with carbon fibre reinforced polymer tape

The cross-section of the reference beam can also be modified during the building operation. Due to the small thickness of the cold-formed steel girder, reinforcement using CFRP tapes was proposed. Commonly available solutions from one of the manufacturers were used in the analyses [2, 3]. The analysed reinforcement solutions are presented in Fig. 2.

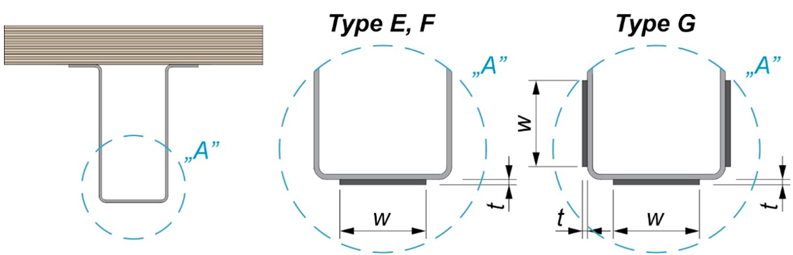

Fig. 2. The cross-sections of the strengthened steel-timber composite beams

Three types of modification were considered: type E with one tape glued to the bottom flange of the steel beam, with stiffness slightly lower than that of steel (CFRP tape type 1) [2], type F with one tape glued to the bottom flange of the steel beam, with stiffness similar to that of steel (CFRP tape type 2) [3], type G with three tapes (CFRP tape type 2), one in the bottom flange, the remaining two on the webs. Various tape lengths L, from 50 to 100% of the beam length, were considered. The design of reinforcing elements can be conducted in many ways [4–8]. In these analyses, the objective function was to obtain the greatest possible increase in the load carrying capacity. The summary of the analysed variants is presented in Table 2.

Table 2. A summary of the strengthening of the girder

Dimension	**Strengthening types and tape types**											
	E1	**E2**	**E3**	**E4**	**F1**	**F2**	**F3**	**F4**	**G1**	**G2**	**G3**	**G4**
	1	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
w, mm	50	50	50	50	50	50	50	50	50	50	50	50
t, mm	1.2	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
L, mm	1500	2000	2500	3000	1500	2000	2500	3000	1500	2000	2500	3000

3. Numerical models

The numerical models of the non-modified beams in the Abaqus and ADINA programs as well as material models were presented in part 1 of the paper [1]. In part 2 of the paper, the numerical models of the modified beams with additional steel sheets or channels, and the beams reinforced with CFRP tapes were developed.

3.1. The model of the modified beam in the ADINA program

The modifications were simulated using 3D solid finite elements. The following interactions were applied (Fig. 3):

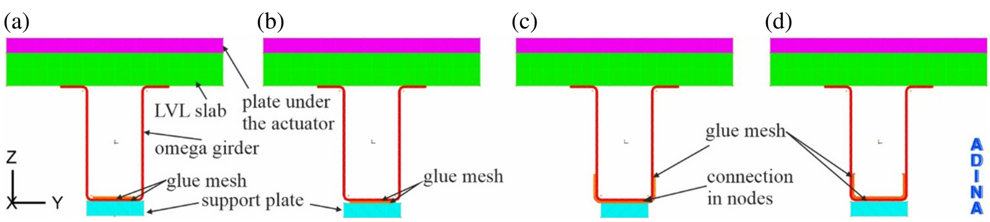

Fig. 3. Girder types in the ADINA program: (a) type A (flat sheet inside), (b) type B (flat sheet outside), (c) type C (U-shaped component outside), (d) type D (U-shaped component inside)

– type A, B, D beams: glue mesh between the omega girder and the additional metal sheet and between the omega girder and the support plates,
– type C beam: glue mesh between the omega girder and the U-shaped component and connection in nodes between the U-shaped component and the support plates.

3.2. The model of the reinforced beam in the abaqus program

The numerical model developed in Abaqus and described in part 1 of the paper [1] was modified to take into account the strengthening with the carbon fibre reinforced polymer tape. Three methods of strengthening were analysed (Fig. 2). Type E and F beams had one CFRP tape (Fig. 4a), whereas type G beam had 3 tapes (Fig. 4b).

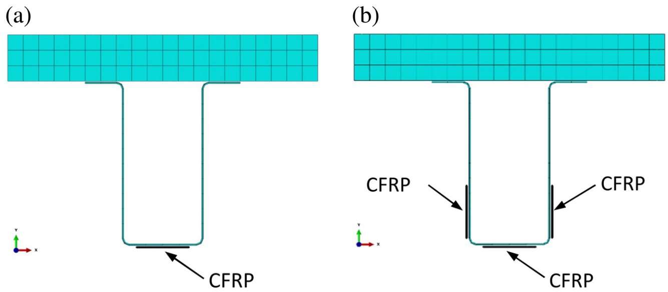

Fig. 4. Girder types in the Abaqus program: (a) E and F, (b) G

The connection between the steel girder and the CFRP tape was modelled as rigid using the tie function in Abaqus. At this stage of the analysis, the thickness and flexibility of the adhesive which connected the tape to the reinforced component was not considered. In the numerical simulations, the reinforcing tape was subjected to load right from the start of the analysis.

4. Results

4.1. The steel-timber composite beam with the modified omega girder

The summary of the results for the steel-timber composite beams with the modified omega girders are presented in Tables 3–5.

Table 3. The results for the modified steel-timber composite beams, type A

Parameter	**Girder types**									
ID	**R**	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**
Elastic load-bearing capacity M_{el}, kN · m	20.90	22.00	23.03	24.70	21.61	23.53	25.44	21.87	24.02	26.16
Plastic load-bearing capacity M_{pl}, kN · m	34.50	36.00	37.47	38.93	36.39	38.25	40.10	36.78	38.95	41.17
Deflection f, mm	7.58	7.58	7.58	7.81	7.35	7.57	7.80	7.35	7.57	7.80
Mass m, kg	56.87	57.18	57.50	57.81	57.26	57.66	58.05	57.34	57.81	58.28
Comparative M_{el}, %	100	105	110	118	104	113	122	105	115	125
Comparative M_{pl}, %	100	104	109	113	106	111	116	107	113	119
M_{el}/m ratio, kN · m/kg	0.37	0.38	0.40	0.43	0.38	0.41	0.44	0.38	0.42	0.45
M_{pl}/m ratio, kN · m/kg	0.61	0.63	0.65	0.67	0.64	0.66	0.69	0.64	0.67	0.71

Table 4. The results for the modified steel-timber composite beams, type B

Parameter	Girder types								
ID	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**
Elastic load-bearing capacity M_{el}, kN·m	21.47	23.14	24.21	21.76	23.70	24.99	21.87	24.09	26.35
Plastic load-bearing capacity M_{pl}, kN · m	36.08	37.54	39.01	36.37	38.26	40.16	36.80	39.00	41.29
Deflection *f*, mm	7.75	7.98	7.98	7.55	7.78	7.78	7.35	7.57	7.80
Mass *m*, kg	57.18	57.50	57.81	57.26	57.66	58.05	57.34	57.81	58.28
Comparative M_{el}, %	103	111	116	104	114	120	105	115	126
Comparative M_{pl}, %	105	109	113	105	111	116	107	113	120
M_{el}/m ratio, kN · m/kg	0.38	0.40	0.42	0.38	0.41	0.43	0.38	0.42	0.45
M_{pl}/m ratio, kN · m/kg	0.63	0.65	0.67	0.64	0.66	0.69	0.64	0.67	0.71

Table 5. The results for the modified steel-timber composite beams, types C and D

Parameter	Girder types					
ID	**C1**	**C2**	**C3**	**D1**	**D2**	**D3**
Elastic load-bearing capacity M_{el}, kN · m	24.52	29.48	34.49	14.35	20.19	22.92
Plastic load-bearing capacity M_{pl}, kN · m	40.28	46.12	51.89	39.80	44.76	49.33
Deflection *f*, mm	7.58	8.03	8.49	4.98	6.14	6.37
Mass *m*, kg	62.49	68.11	73.73	62.42	67.97	73.52
Comparative M_{el}, %	118	141	165	69	97	110
Comparative M_{pl}, %	117	134	151	115	130	143
M_{el}/m ratio, kN · m/kg	0.39	0.43	0.47	0.23	0.30	0.31
M_{pl}/m ratio, kN · m/kg	0.64	0.68	0.70	0.64	0.66	0.67

A reference beam (*R*) analysed in part 1 of the paper [1] was added to each table. The deflection (*f*) corresponded to the elastic load-bearing capacity. The comparative M_{el} and M_{pl} were determined as the ratio of the result for an individual beam to the result for the reference beam. The parameter determining the degree of cross-sectional effort was assumed as the ratio of the load-bearing capacity to the mass.

The results of the M_{el}/m and M_{pl}/m ratios as well as the comparative M_{el} and M_{pl} are presented in the form of graphs (Figs. 5 and 6).

When comparing type A beams with the corresponding type B beams, i.e., with identical sheets, very small differences were observed in favour of the type B section. Very similar relationships between the results for the beams were observed in groups A and B. In group A, the most desirable cross-sectional effort was achieved for cases A3, A6 and A9, i.e., with 3×60 mm sheets. The elastic load-bearing capacity for such beams was 24.70 kN · m, 25.44 kN · m and 26.16 kN · m, respectively. For these cases, the comparative M_{el} values were 118%, 122%,

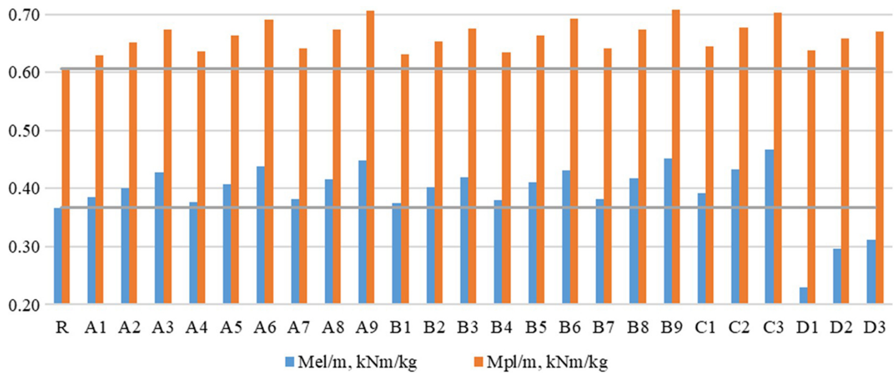

Fig. 5. The ratios of load-bearing capacity to mass for the modified beams

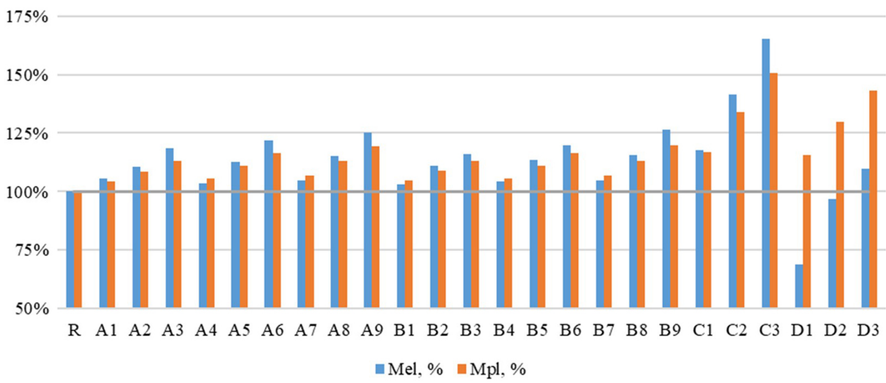

Fig. 6. The comparative elastic and plastic load-bearing capacities of the modified beams

and 125%, respectively. In the case of beams C2 and C3 with 2- and 3-mm C-sections, the comparative load-bearing capacity M_{el} was 141% and 165%, respectively. At the same time, these cross-sections showed large M_{el}/m ratios of 0.43 and 0.47. Type D beams turned out to be the least effective, as their elastic load-bearing capacity was comparable to, and sometimes lower than, the elastic load-bearing capacity of the non-modified reference beam.

4.2. The steel-timber composite beam strengthened with the carbon fibre reinforced polymer tape

Table 6 shows the results for beams reinforced with CFRP tapes.

The values of the M_{el}/m and M_{pl}/m ratios, and of comparative M_{el} and M_{pl} were presented in Figs. 7 and 8.

The parameters and symbols used were consistent with Chapter 4.1. The use of the tape resulted in the increase in the load-bearing capacity, both in the elastic and plastic range. The shortest tape, i.e., 50% of the beam length, was selected to cover the yield zone between

Table 6. The results for the reinforced steel-timber composite beams, types E, F and G

Parameter	Strengthening types												
	R	**E1**	**E2**	**E3**	**E4**	**F1**	**F2**	**F3**	**F4**	**G1**	**G2**	**G3**	**G4**
Elastic load-bearing capacity M_{el}, kN · m	20.9	22.44	22.56	22.59	22.72	23.63	23.79	23.84	23.99	26.47	26.50	26.61	26.89
Plastic load-bearing capacity M_{pl}, kN · m	36.1	45.99	46.00	46.73	52.25	46.00	45.95	46.80	53.45	45.96	45.93	47.12	94.98
Deflection *f*, mm	7.81	7.93	7.94	7.94	7.95	8.20	8.21	8.21	8.22	8.59	8.61	8.47	8.49
Mass *m*, kg	56.87	57.43	57.62	57.81	58.00	57.46	57.65	57.85	58.05	58.63	59.22	59.81	60.40
Comparative M_{el}, %	100	107	108	108	109	113	114	114	115	127	127	127	129
Comparative M_{pl}, %	100	127	127	130	145	127	127	130	148	127	127	131	263
M_{el}/m ratio, kN · m/kg	0.37	0.39	0.39	0.39	0.39	0.41	0.41	0.41	0.41	0.45	0.45	0.44	0.45
M_{pl}/m ratio, kN · m/kg	0.63	0.80	0.80	0.81	0.90	0.80	0.80	0.81	0.92	0.78	0.78	0.79	1.57

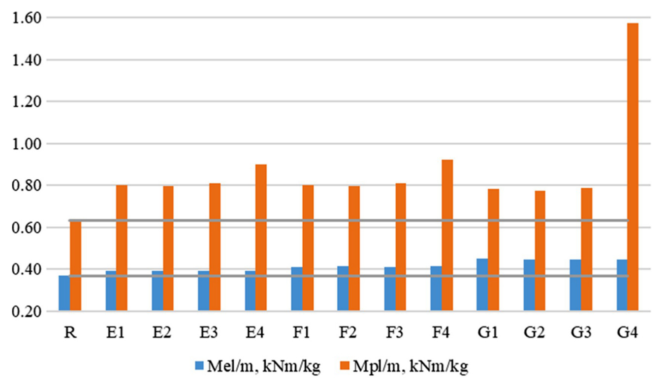

Fig. 7. The load-bearing capacity to mass ratios for the reinforced beams

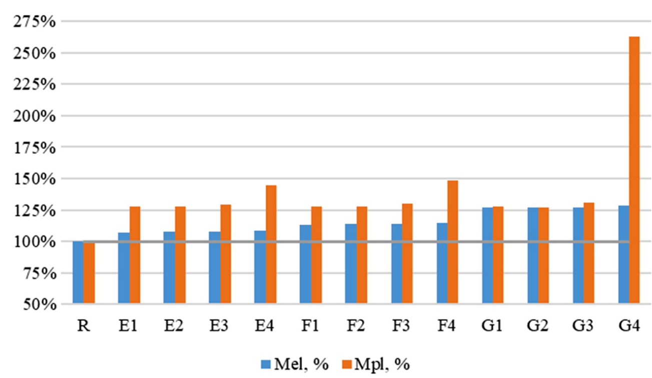

Fig. 8. The comparative elastic and plastic load-bearing capacities of the reinforced beams

the two concentrated forces. Increasing the length of the tape was not effective and did not significantly increase the load-bearing capacity because of the failure mode type. For the beam types with the reinforcement tape shorter than the length of the beam (E1–E3, F1–F3, G1–G3), the yield strength of the steel was achieved not only in the middle of the omega girder but also at its support zone, as shown in Fig. 9.

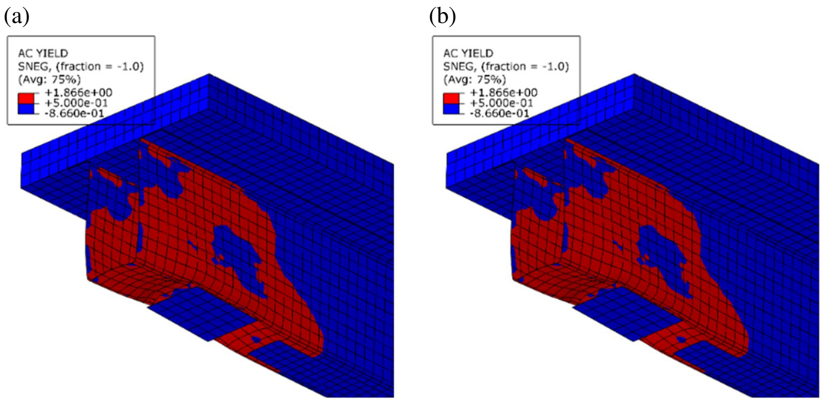

Fig. 9. The yield strength of the steel achieved at the support zone: (a) type F3 beam, (b) type G3 beam

The additional reinforcement of the support zone may provide for a greater load-bearing capacity of the beam. The use of the tapes matching the length of the beam (types E4, F4 and G4) resulted in a significant increase in the plastic load-bearing capacity. However, the use of the reinforcement along the entire length of the beam at the building operation stage is very difficult and expensive.

5. Discussion

In the case of the modified steel-timber composite beams, the following findings were observed. Although type B beams have the additional metal sheet placed outside the omega girder and therefore have a larger moment of inertia than type A beams, when comparing type A and B beams, very small differences were observed in favour of the type B section. In some cases, type B beams achieved worse results than type A beams, which stemmed from the adopted time step and the measurement of plastic deformations at individual steps. It should be noted that the authors decided to apply a one-time step to all the analysed beams. This will allow for automating the calculations for cross-section optimization, which will be planned at a later stage of testing. However, the type A modification was considered more advantageous than the type B modification because the sheet metal was located inside the omega section. Such a solution helps to increase the aesthetics of the beam. By design, omega is a closed cross-section, and therefore the surface of the sheets inside the cross-section is not visible. The A3 and A9 cross-sections with 1- and 3- mm sheets deserve the most attention. The elastic load-bearing capacities for beams R, A3 and A9 are 20.9 kN · m, 24.70 kN · m and

26.16 kN · m, respectively. The C2 and C3 sections modified with channels can be used where higher load-bearing capacities are required (M_{el} equals to 29.48 kN · m and 34.49 kN · m). However, their mass was approximately 20–30% greater than the mass of the reference beam. The D-type beams were heavier (20–30%) than the reference beam and therefore less efficient. Their load-bearing capacities were similar to the results for the reference beam, because stress concentration occurred on the lower flange, especially in the area of the small bending radii of the C-section (Fig. 10).

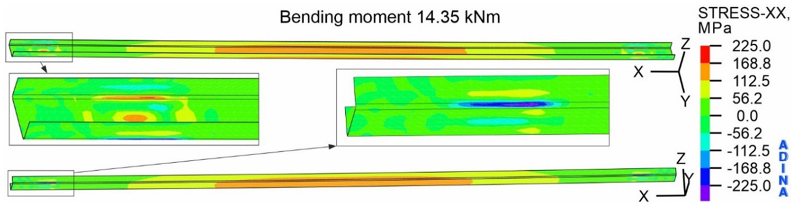

Fig. 10. The yield strength achieved at the C-shaped reinforcement in D1 beam

When making the D-beam, the limitations resulting from the small bending radius must also be taken into account. The authors are planning to carry out experimental tests of the analysed composite beams. It is necessary to consider the connectors between the steel girder and the LVL slab. Furthermore, when considering modifications of the cross-section, the possible ways of connecting the steel sheets should be taken into account, including resistance spot welding [9, 10] and refill friction stir spot welding [11, 12]. When selecting the method for joining the sheets, it is necessary to consider not only the process parameters, but also the location of the welds. Modifying the cross-section using channels poses a particular challenge.

In the case of the reinforced beams, the use of the tape resulted in increased load-bearing capacity. Due to the problem with the yielding of the support zone, the increase of the load-bearing capacity for type E1–E3, F1–F3, G1–G3 beams was similar (27–31%). The use of tapes matching the length of the beam (types E4, F4 and G4) may provide for a greater increase of the beam's load-bearing capacity (45–163%). However, the use of reinforcement along the entire length of a beam at the building operation stage may be a problem. Furthermore, the reinforcing tape was subjected to load from the start of the numerical analysis. When an existing structure is being reinforced, it is always impacted by certain loads, for example its own weight and part of the live load. In such situations, reinforcing components begin to cooperate when there is a certain state of stress and deformation in a beam. The impact of this load on the effectiveness of the reinforcing process may be the subject of a separate study.

6. Conclusions

In part 2 of the paper, modified steel-timber composite beams with cold-formed omega girders were investigated. The findings of this investigation are provided below:

– In the case of the modified steel-timber composite beams, the highest increase in the load-bearing capacity was observed for the modification in form of a channel placed outside the omega girder (C3). However, the mass of the modified beam with the channel was 29.6% greater than the mass of the reference beam. Furthermore, the modifying the girder using channels poses a particular challenge. For this reason, the modifications in the form of a flat sheet placed inside or outside the omega girder can be used instead of the channel. The sheet metal located inside the omega section helps to increase the aesthetics of the beam.

– In the case of the reinforced steel-timber composite beams with CFRP tapes, the use of the tape resulted in increased load-bearing capacity. The increase of the load-bearing capacity for type E1–E3, F1–F3, G1–G3 beams was similar (27–31%) because of the yielding of the support zone. The use of tapes matching the length of the beam (types E4, F4 and G4) may limit the problem of the yielding of the support zone. However, the use of reinforcement along the entire length of a steel-timber composite beam at the building operation stage may be difficult and expensive.

The investigation presented in this paper has certain limitations described in part 1 of the paper [1]. Furthermore, in the case of the carbon fibre reinforced polymer tape analysed as a method of beam reinforcement at the building operation stage, the impact of the existing load on the effectiveness of the reinforcing process was not taken into account. When an existing structure is reinforced, it is impacted by certain loads. This impact may be investigated in a separate analysis. What is more, the thickness and flexibility of the adhesive which connected the tape to the steel girder was not considered.

The presented study was only a preliminary evaluation of the load-bearing capacity of the steel-timber composite beams with modifications or reinforcing. The laboratory tests are necessary to verify and develop more advanced numerical models.

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Badania numeryczne belek zespolonych stalowo-drewnianych z dźwigarami zimnogiętymi o przekroju w kształcie litery omega. Część 2: Belki z modyfikacjami oraz belki wzmocnione

Słowa kluczowe: belki zespolone stalowo-drewniane, drewno klejone warstwowo z fornirów (LVL), kompozyt CFRP, przekroje w kształcie litery omega

Streszczenie:

Artykuł stanowi drugą część badań numerycznych belek zespolonych stalowo-drewnianych z dźwigarami zimnogiętymi o przekroju w kształcie litery omega oraz z płytami z drewna klejonego warstwowo z fornirów. Po przeprowadzeniu wstępnej analizy przekroju belki zespolonej w pierwszej części pracy, zaproponowano modyfikację jej przekroju oraz sposób jej wzmacniania w drugiej części pracy. W celu zwiększenia nośności na zginanie belki zespolonej zaproponowano modyfikacje polegającą na dodaniu blachy stalowej wewnątrz przekroju dźwigara lub ceownika na zewnątrz jego przekroju. Modyfikacje te mogą być wykonane na etapie produkcji stalowych dźwigarów. Modyfikacja w postaci ceownika umieszczonego na zewnątrz przekroju omega doprowadziła do największego wzrostu nośności. Jednak masa belki zmodyfikowanej za pomocą ceownika była o 29,6% większa niż masa belki referencyjnej. Ponadto, modyfikacja dźwigara za pomocą ceownika może być trudna do wykonania, dlatego zamiast ceownika można wykorzystać blachę. Ze względów estetycznych, blacha może być umieszczona wewnątrz przekroju dźwigara. Dodatkowo, oceniono efektywność wzmacniania belek zespolonych za pomocą taśm wykonanych z kompozytu CFRP na etapie eksploatacji budynku. Wykorzystanie taśm doprowadziło do wzrostu nośności na zginanie. Jednak wzrost ten może być ograniczony ze względu na uplastycznienie strefy podporowej belki.

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