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Aluminium alloy girders strengthened by steel elements

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Preliminary report

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Aluminium alloy girders strengthened by steel elements

When used as construction materials, the aluminium and its alloys are dominant in the field of façade structures. In these applications, a need has been felt in practice to strengthen façade structures made of aluminium alloys, and the steel is also used for such strengthening. A review of current possibilities is presented in the paper from theoretical and practical standpoints. An original solution involving gluing of steel elements is presented as an optimum technical solution. The solution has been proven by testing a sample in laboratory conditions, and it constitutes a basis for detailed research, which is currently under way.

Ključne riječi:
aluminium alloys, composite girders, gluing, cross-sectional bearing capacity, girder deformation

Prethodno priopćenje

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Nosači od aluminijskih legura ojačani elementima od čelika

Aluminij odnosno aluminijske legure kao materijal u građevinarstvu dominiraju u području fasadnih konstrukcija. U ovim primjenama se u praksi pojavljuje potreba da se fasadni nosači od aluminijskih legura ojačaju pri čemu se to izvodi i elementima od čelika. U radu je napravljena rekapitulacija mogućnosti s teorijskog i praktičnog aspekta. Kao jedno od optimalnih tehničkih rešenja predloženo je originalno s lijepljenjem čeličnih elemenata. Rješenje je potvrđeno pokusnim ispitivanjem na jednom uzorku u laboratorijskim uvjetima i osnova je detaljnijih istraživanja koja su u tijeku.

Ključne riječi:
aluminijske legure, spregnuti nosači, lijepljenje, nosivost presjeka, deformacija nosača

Vorherige Mitteilung

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Mit Stahlelementen verstärkte Träger aus Aluminiumlegierungen

Aluminium beziehungsweise Aluminiumlegierungen dominieren im Bauwesen auf dem Gebiet von Fassadenkonstruktionen. Bei solchen praktischen Anwendungen besteht der Bedarf, die Fassadenträger aus Aluminiumlegierungen zu verstärken. Dazu werden unter anderem Stahlelemente verwendet. In dieser Arbeit werden dazu verschiedene Möglichkeiten in theoretischer und praktischer Hinsicht rekapituliert. Als ein optimales technisches Konzept wird das Aufkleben von Stahlelementen vorgeschlagen. Diese Lösungsmöglichkeit wurde mit Testversuchen an einer Probe unter Laborbedingungen bestätigt und dient als Grundlage für laufende detailliertere Untersuchungen.

Ključne riječi:
Aluminiumlegierungen, Verbundträger, Klebewirkung, Querschnittswiderstand, Trägerverformung

1. Introduction

Many books and lectures in the field of reinforced concrete structures and composite steel and concrete structures start with conclusion that fortunate fact, that coefficients of thermal expansion of concrete and steel are almost identical, is accounted for development of these areas. As mentioned above, in combination with essentially different coefficients of thermal expansion of aluminium and steel and well known problem of contact corrosion between these two materials, and engineering intuition itself, have blocked for a long time any thought or attempt in construction engineering to combine aluminium and steel, as well as materials with different coefficients of thermal expansion in general.

However, for long time we have witnessed successful examples of combining materials of various thermic features such as steel and aluminium in other areas of engineering creativity, especially in aerospace and ship building industries, but also in the industry of a variety of composite materials or products, for example of the panels for different applications, including the construction industry.

The automotive industry, for more than a decade develops the body which is a combination of castings, profiles and sheets of aluminium and steel. The strategic commitment to this has resulted, in the meantime, in creation of a largely aluminium bodies. In Figure 1, taken over from [1], is presented a body of ten-year-old model of AUDI, which is a combination of aluminium and steel materials. From this picture can be concluded that the connections must be carried out in a manner that definitely couples aluminium and steel into unique structure, although component materials are separated and form separate units of this body. It is clear that the problems resulting from the coupling of aluminium and steel, such as essentially different coefficient of thermal expansion, contact corrosion and problems connecting these two materials, are somehow overcome or compensated to ultimate effect, at economically acceptable manner. Considering the reputation of the company, it is unlikely that any compromise at the expense of quality has taken place

In an attempt to combine the good properties of aluminium and steel researchers were able to create usable composite panels [2] in the form of laminated sheets, so that with one or both sides of the steel sheet, in the process of rolling, they bond aluminium alloy sheets. In this way, the laminated panels are obtained with favourable characteristics compared to pure aluminium or pure steel panels with the same targeted features. Researchers, however, in the published works discreetly note that the tests were conducted at room temperature meaning that the impacts of temperature changes have not been analysed.

The previously mentioned trends have imposed the need for research on the topic of connecting aluminium and steel. Studies and published papers have appeared, including [3], dealing with, at first sight hard to imagine, method of welding steel and aluminium. It is clear that finding optimal welding procedure is still in progress but, in general, it is possible to say that it is proven that the welding aluminium for steel in the technically and economically acceptable way can be accomplished.

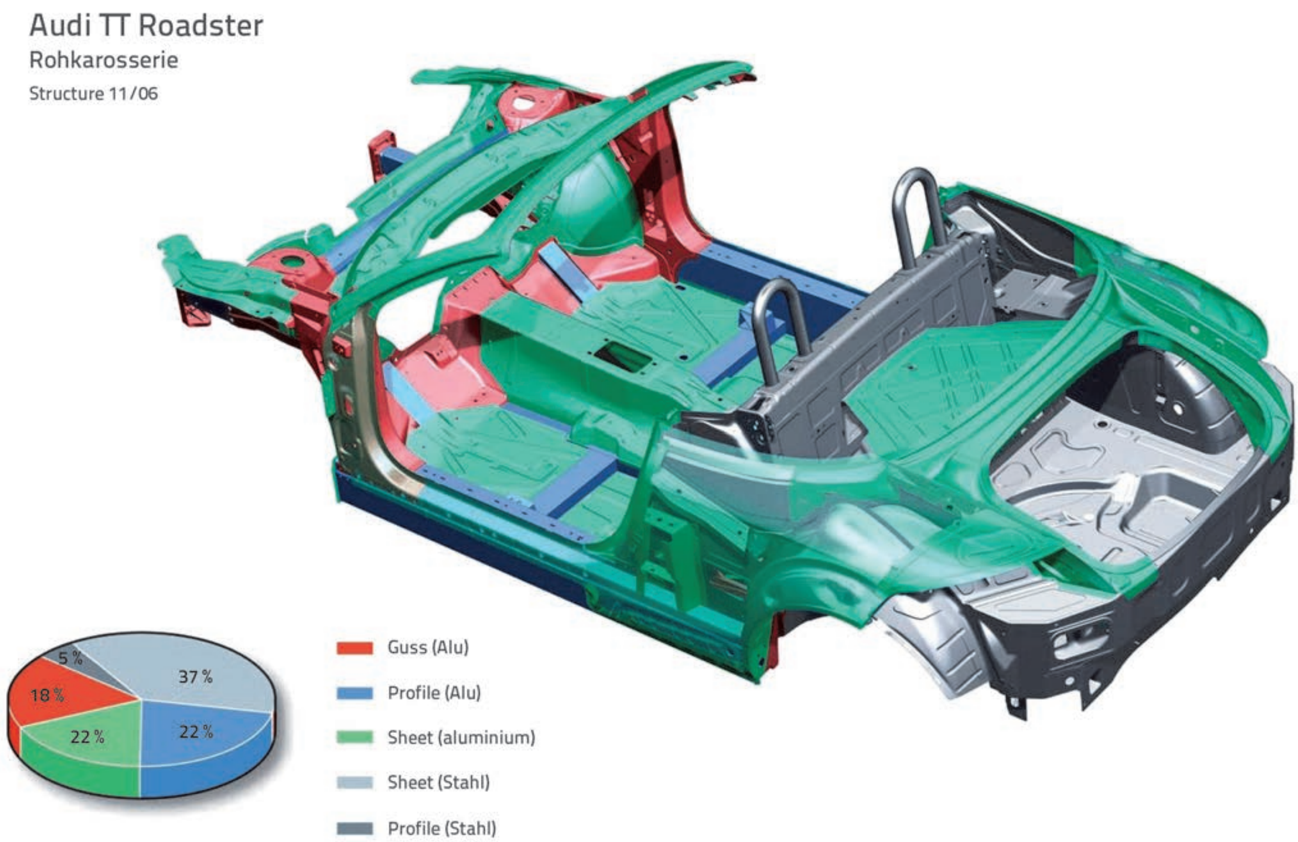


Figure 1. The body of the Audi TT as hybrid aluminium and steel parts

Despite clear activities in research on issues of merging and combining aluminium and steel in other engineering fields, research of literature in the field of structural engineering indicates that in construction industry, this theme is neglected. Apart from some attempts in research on beams formed by combination of aluminium alloys and steels conducted at the University of Glasgow, Scotland, which resulted in a series of interconnected papers [4-6], and one relatively recent professional book [7], in the research of literature in English other experiences have not been encountered. Researchers from the University of Glasgow have examined bi-axially bended cantilever beam formed by connecting a tube profile of aluminium alloy with inserted cold-formed steel "U" profiles. Connections were carried out asymmetrically by screws on the rib, and during tests the manner of adjusting steel profile inside the tube of aluminium alloy has been varied. The research results do not point to a significant advantage of composite section expressed in relation to the simply combined cross-section. Temperature changes are not considered in the study. In the authoritative book [7], the authors Kissell and Ferry cite many examples of combining aluminium with other materials, including aluminium with wood and concrete. Thereby they mostly point to the analysis of the performance cases and calculations of combining aluminium alloys and steel. An entire chapter of the book is devoted to an issue of the symmetric and asymmetric coupling of aluminium alloys and steels, including impacts of temperature changes. Without going into economic analysis, the authors state that the application can be found where the same can have economic sense, i.e. where the obvious advantages in terms of capacity and deformability will not be compromised by the influence of temperature changes.

2. Examples from practice

Aluminium alloy as a material for building structures are used in various fields, [8-10], and one of the areas where it arises as practically sole remedy, is construction of glass façades. During design and implementation of various façades with aluminium alloy structures in engineering practice and catalogues of different manufacturers, quite uniform methods of overcoming the situations that somehow deviate from the typical situation for which a façade was designed, and for which mullions of aluminium alloys with usual tube cross-section was designed can be encountered relatively often. Such reinforcements do not include composite action of two materials.

If focuses only on solutions where there exists an additional profile of steel, as there are system solutions with the insertion of aluminium profiles, then the usual reinforcement of façade's aluminium alloy mullions by steel can recapitulate with solutions shown in Figure 2. Common to all solutions of this type is that, at least declaratively, no strengthening is connected with the basic profile of mullion, and that the hybrid beam works as a simple sum of component beams. However, the authors of this paper, during the years of practice have been ensured that during execution various forms of unplanned connections between aluminium alloy and steel beams appear, in the most of the cases as the result of installing self-drilling screws at connections for the transoms of façade system, i.e., for installation of wind battens and other components of the façade system. There are examples that this is planned as such, as contractors state, to avoid in assembly process falling out of steel profile reinforcements from the basic aluminium alloy profile. It must be said that the authors track the exploitation of some of such façades realization which were known for unplanned and uncontrolled composite action between aluminium alloy and steel, and no functional impairments were noticed.

Calculation of such solutions as they are declaratively designed, without composite action, is simple. Since by adjusting beams made of aluminium alloy and steel are forced to share a common deformation equating the terms for bending, for example, for the simple beam loaded by evenly distributed load q, easily, from equation (1), can determine the appropriate parts of total load carried by combined beam components parts of aluminium alloy, (q_a), or of steel, (q_s). In these terms is used the fact that the ratio between the modulus of elasticity of steel and aluminium alloy, E_s = 210000 MPa and E_a = 70000 MPa, is the constant $E_s/E_a=3$, while codes I_a and I_s relates to individual moments of inertia of aluminium or steel part of the combined cross-section. Further calculations, practically, can proceed independently according to the regulations on appropriate materials.

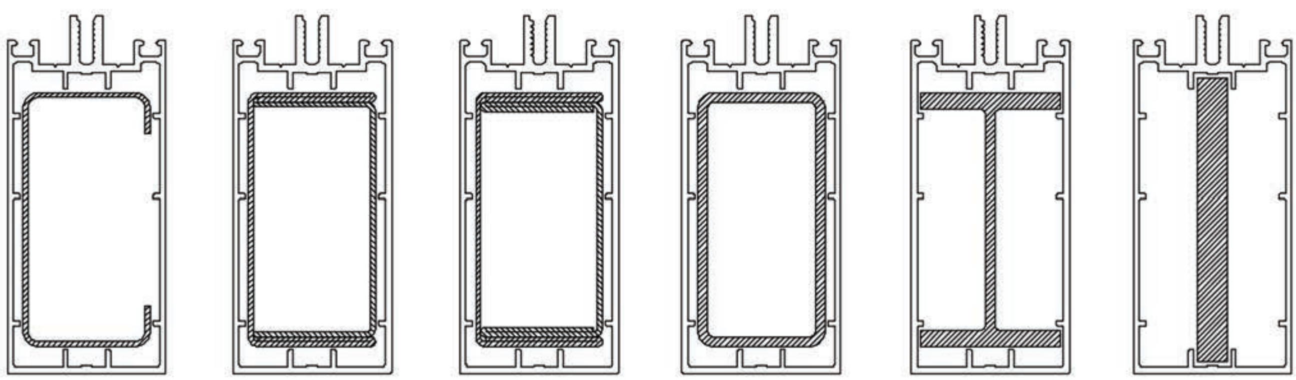


Figure 2. Examples of planned reinforcements from the producer's catalogue of façade systems

$$q_s = q\frac{3\frac{I_s}{I_a}}{1+3\frac{I_s}{I_a}} \quad \text{respectively} \quad q_a = q\left(1-\frac{3\frac{I_s}{I_a}}{1+3\frac{I_s}{I_a}}\right) \qquad (1)$$

Beyond pure engineering curiosity as a motivation for research, the possibilities of composite steel and aluminium elements during the design of beams in structures, it has to be supposed that technically efficient solution would probably provide important economic advantage for several reasons. Due to metallurgical (extrusion), physical and mechanical (corrosion resistance and small specific gravity) and aesthetic (anodizing) properties of aluminium alloys which were imposed as dominant material for specific structures, such as, among other, the façade systems. In the case of mullions, or other elements mainly exposed to bending, a significant disadvantage of aluminium alloys represents small modulus of elasticity and, in combination with this, technological limitations in terms of dimensions of extruded profiles that are limited by capacity of extrusion presses. The consequence of the previous is that during design of cross sections i.e., designing of beams the most often respected is deformation and usually is not possible to design an optimised cross sections. Although this paper does not deal with the economic aspects, it is likely that beams in the composite combinations of aluminium alloy and steel could be economically justified with regard to the price per unit of mass of profile of aluminium alloys which is 5-7 times higher than of steel.

It is interesting that the situations with combined beams of aluminium alloys and steel, as obviously often used in practice, are not covered by contemporary codes. Furthermore, from the final version of existing code for aluminium structures, EN 1999-1-1:2007+A1 [11], are deleted the articles concerning this matter, but which had been in content of former versions of the same standard [12, 13] as the base for the relatively often incompletely documented applications in practice.

3. The influence of temperature change

In the classical theory of composite structures developed for combinations of concrete and steel needs, the impact of temperature changes is irrelevant due to fact that these materials, concrete and steel, have almost the same coefficient of thermal expansion. In the case of aluminium–steel combination we have one of the highest differences in values of coefficients of thermal expansion among materials convenient for the engineering structures in general. The coefficient of thermal expansion in the case of aluminium and aluminium alloys, which is according to [11] is $\alpha_a = 2{,}3 \times 10^{-5}$ 1/°C, is almost double than in case of steel, which according to [14] is $\alpha_s = 1{,}2 \times 10^{-5}$ 1/°C. This fact is not possible to ignore during any research in regard to the matter of hybrid or composite structures made by combination of these two materials, in spite the fact that in almost all papers quoted in preface just that is done.

In this paper a brief analysis has been conducted on behaviour of composite element composed of aluminium and steel parts regarding temperature changes as partially taken over from references [7] and transformed by the authors original analyses that allow certain conclusions in aim to use it for defining the problem in further examinations.

Analysis is of composite bar of aluminium and steel profile which individual centres of gravity and total centre of gravity are reciprocally coincided as well with connection plane centre of gravity. An idealised example of such case is given in Figure 3. For this case, theoretically, connection upon length is not of importance but only edge conditions at bar ends which must be such that end cross-sections must dilate equally. The bar is not exposed by any loads but temperature change only.

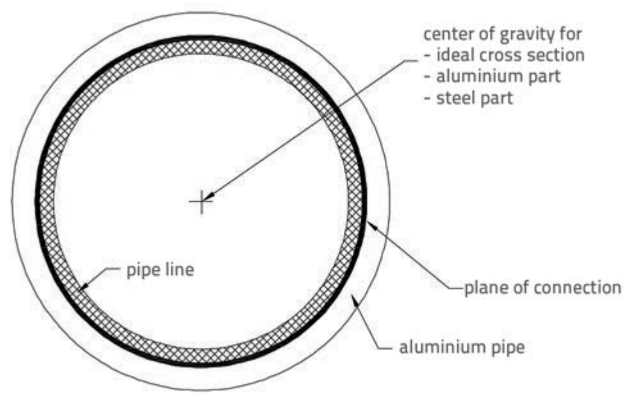


Figure 3. Idealised rod of symmetrical stiff coupling cross-section of aluminium and steel

During, for example, heating it is clear that composite bar tends to elongate. Therefore is clear that, regarding achieved end conditions, aluminium and steel components must elongate by the same value. Aluminium component of the rod has tendency to elongate more than steel one, but in some way it is limited. i.e., compressed by the steel component of cross-section; and vice versa, the steel component of the cross-section tends to elongate less than the aluminium one but, regarding the fact that elongation must be equal, aluminium profile exposes the steel one to tension. During this, due to heating, certain compression stress appear in aluminium component of the composite cross-section, or to corresponding tension stress in steel component of the composite cross-section. During the cooling the situation is, of course, opposite. Taking into account that external forces do not affect the bar, it is clear that the compression force in aluminium component of cross-section and tension force in steel component of the cross-section must be in balance meaning of the equal intensity and opposite sign.

Equalizing the formulas for independent elongation of aluminium and steel components of the composite cross-section and from the balance of forces affecting the composite bar, it is possible to determine analytically the final elongation, ε_f of composite bar for temperature change ΔT_u as well as stresses that appears during this in aluminium, σ_a, or steel,

σ_s, component of the composite cross-section. Corresponding formulas, taken over from [7] and adapted by mathematical transformations, are given in equations (2):

$$\varepsilon_i = \Delta T_u \frac{\alpha_a A_a E_a + \alpha_s A_s E_s}{A_a E_a + A_s E_s}$$

$$\sigma_a = \Delta T_u (\alpha_a - \alpha_s) \frac{E_a A_s E_s}{A_a E_a + A_s E_s} \quad (2)$$

$$\sigma_s = \Delta T_u (\alpha_s - \alpha_a) \frac{E_s A_a E_a}{A_a E_a + A_s E_s}$$

Treating as constant the modules of elasticity and coefficients of thermal expansion of aluminium alloy and steel is possible, by mathematical transformations, to gain an equation (3) based on which is possible to determine imaginary coefficient of thermal expansion of the ideal cross-section, α_i, as well as stresses generated by temperature change in components of the cross-section in the forms convenient for parametric analysis, in the ratio function of steel cross-section area, $\boldsymbol{A_s}$, and aluminium alloy cross-section area, $\boldsymbol{A_a}$, i.e., the only one variable which is the matter of choice while designing, $\boldsymbol{A_s/A_a}$. In the formulas of showed equations (3) stresses and temperature changes are treated with absolute values.

$$\alpha_i = \frac{\alpha_a A_a E_a + \alpha_s A_s E_s}{A_a E_a + A_s E_s} = \alpha_a \left(\frac{1 + 1{,}565 \frac{A_s}{A_a}}{1 + 3 \frac{A_s}{A_a}} \right)$$

$$|\sigma_a| = 2{,}31 \cdot |\Delta T_u| \frac{\frac{A_s}{A_a}}{1 + 3 \frac{A_s}{A_a}} \ \text{[MPa]} \quad (3)$$

$$|\sigma_s| = 2{,}31 \cdot |\Delta T_u| \frac{1}{1 + 3 \frac{A_s}{A_a}} \ \text{[MPa]}$$

Above given equations provides comfortable parameters analysis and represent the original contribution to the theory of composite structure in general. Former conclusion is derived after comprehensive research of the available literature, not only in the field of composite steel and aluminium structures, but the composite structures of two different materials in general.

Under analysis is the most often used aluminium alloy for façade constructions, 6060-T5 t ≤ 5mm with 0,2 % proof strength $f_{ay} = f_o = 120$ MPa and steel S355 with yield strength $f_{sy} = f_y = 355$ MPa. The parameter ΔT_u varies with values common with structural engineering of approximately ±15 °C for indoor structures, ±30 °C for outdoor structures, ±50 °C as the most common, according to the authors too high, request for façade constructions, and ±100 °C and ±200 °C for purely theoretical reasons, regarding the matter of behaviour at high temperatures with these values, which is out of this paper's scope. The variable $\boldsymbol{A_s/A_a}$ credibly can fit the range A_s/A_a = 0,1-0,8. It could be assumed that for lower values probably appears the problem of feasibility, and for higher values that, somehow, discontinues as reinforced aluminium profile and continues as reinforced steel profile. For mere theoretical reasons, adopted is the range A_s/A_a = 0,001-1000. With chosen parameters as such and variable range, using equations (3) at Figure 4, are in logarithm scale showed diagrams of relative stresses $\sigma_{i,\Delta Tu}/f_{i,y}$ in function of variable $\boldsymbol{A_s/A_a}$ with an idea to, while using an actual example, perceive which part of capacity approximately occupies the temperature change $\boldsymbol{\Delta T_u}$, with composite bar composed of thermally variable component materials.

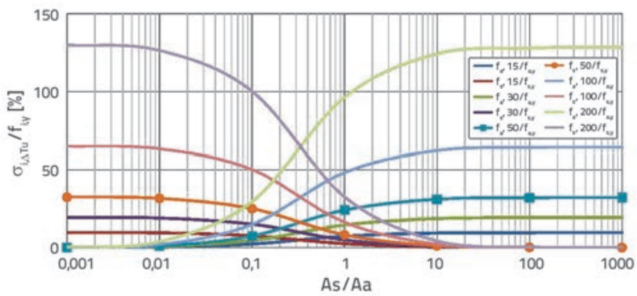


Figure 4. Relative stresses in component parts of the composite cross-section for various temperature changes in ratio function of cross-section areas for combination of materials AW6060-T5- t≤5/S355

It can be proven, by comparing analogous diagrams in combination with steel S235, that steel S355 would be better choice in situations when capacity is competent, because then the ratio $\boldsymbol{f_{s,y}/f_{a,y}}$ is close to the ratio $\boldsymbol{E_s/E_a}$ meaning the grades of capacity compromising of material during temperature change are more balanced. However, this does not need to be important when deformation is competent, which is most often the case in applications that have initiated this research because in that case the resistances are unused. Diagrams in figure 4 and equation (3) can result in one interesting conclusion. Namely, there is an ultimate value for each pair of coupling materials with different coefficients of thermal expansion and actual temperature change, to which stresses provoked in a function relation of cross-section areas of component materials tend. Diagram can also result in conclusion that for the actual pair of materials, the aluminium alloy 6060-T6 and steel S355, and for temperature changes usual in structural engineering of ΔT_u = ±15-50 °C, cannot come to exhausting either of the component materials in any cases, even theoretically.

In analysed case the impacts provoked by temperature changes for values usual in structural engineering of ΔT_u = ±15-50 °C, are acceptable. The impacts of temperature changes expressed relatively in regard to the 0,2 % proof stress, i.e. yield stress of component materials are in 10 %-30 % range. In true feasible range of relations of cross-section areas of component materials in composite cross section A_s/A_a = 0.1-0.8, this

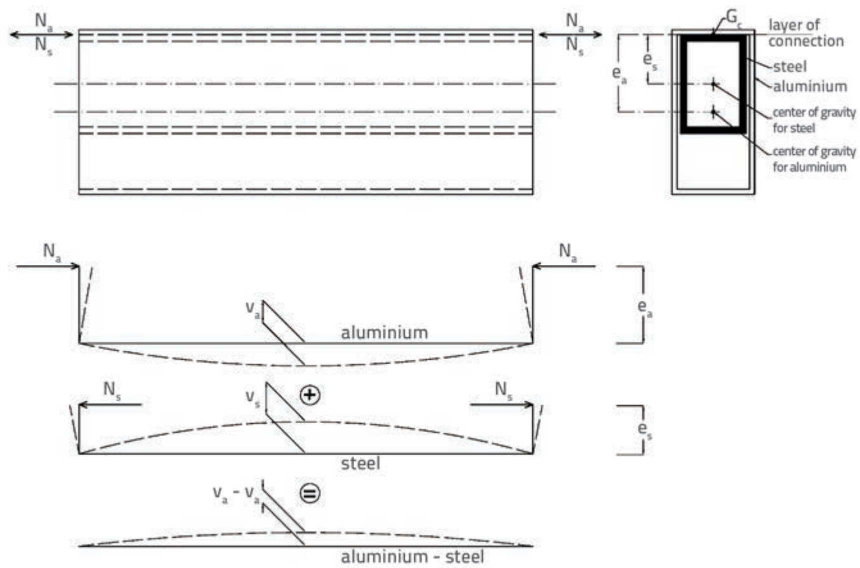


Figure 5. Deformation of the unsymmetrically composite bar due to temperature change

measure is even lower for about 3 %-25 %. This conclusion indicates that successful application of aluminium and steel composite structure is possible, and the contribution of aimed characteristics which are desired by coupling is good enough when it is higher than 25 % compared to equivalent characteristics of basic beam which is being reinforced. In analysed applications the aimed characteristic for reinforcement is, as mentioned already, stiffness, i.e. deformation of beams so, thanks to three times larger module of elasticity of steel relating to aluminium alloy, it is realistic to expect advantages significantly higher than disadvantages due to different coefficients of thermal expansion.

It is possible to detect that intensity of the pair of axial forces of opposite value generated by temperature change in component materials of composite cross-section, is practically known value for adopted areas of component materials, and can be expressed in the form showed in the equation (4) as deduced from equation (3) for tension stress in aluminium part of cross-section.

$$|N_s| = |N_a| = |\sigma_a| A_a = 0{,}231 \cdot A_a |\Delta T_u| \frac{\frac{A_s}{A_a}}{1+3\frac{A_s}{A_a}} \text{ [kN]}, \quad A_a \text{ in cm}^2 \qquad (4)$$

It should be kept in mind that applying points of axial forces induced by temperature change, which are of opposite value, or in balance reciprocally, is in centre of gravity of connection planes at the bar ends. If the connection planes centre of gravity does not coincide with individual centres of gravities of composite materials, or with centre of gravity of ideal cross-section, then temperature change produces a bending moment which, in general case, impacts the cross section resistance and deformation of the bar. In theory, these impacts can be eliminated only if individual centres of gravities of component materials are at the same side of connection planes centre of gravity, and if the condition is fulfilled that individual eccentricity of component materials in relation with connection planes centre of gravity is proportional to its stiffness, i.e. when $e_a/(E_a I_a) = e_s/(E_s I_s)$, which is hard to reach in practice. In all other cases temperature change at the composite bar with no external forces provokes, beside axial forces, bending moment i.e. causes deformation of the bar.

In Figure 5 is an attempt made to explain the former quotations using graphic expression of imagined component and real resulting deformations at example of unsymmetrically compound aluminium and steel composite beam. The picture also contains explanations of introduced marks for individual eccentricities of component parts of composite cross-section. Similar analogy can be applied to describe the bending moment i.e. stress conditions. From the same picture can be noticed that unsymmetrical arrangement, at which individual centres of gravities of component materials are at opposite sides of connection planes centre of gravity, always would bring to the situation where deformation tendency of component materials interferes due to generated influences by temperature change, i.e. such solutions of reinforcements can hardly be acceptable from technical point of view.

4. Possibilities of the aluminium alloys beams steel reinforcement

Theoretically, it had been explained that disadvantages due to different coefficients of thermal expansion of analysed pair of materials are of such order of magnitude that composite action of this two materials would make most sense if materials arrangement is symmetrical, if realised with small ratio A_s/A_a and if resulting with improvement of targeted characteristics significantly higher than 25 %.

As possibilities for reinforcement of aluminium alloys beams by steel solutions expressed at Figure 6 are analytically examined. The examined solution include, for comparison reasons, a solution with insertion of steel tube with no composite actions, a solution with insertion of aluminium tube with no composite action, and solution with specially designed profile of aluminium alloy of the same height.

The case (a) of the Figure 6 is a simulation of solution from Figure 2, with no composite action, where in practice along the length sporadically the adjusted pads are bonded for inserted profile which, except that it serve for adjustment, i.e. providing the equivalence of deformations, have also the function of separating the steel and aluminium aiming to prevent contact

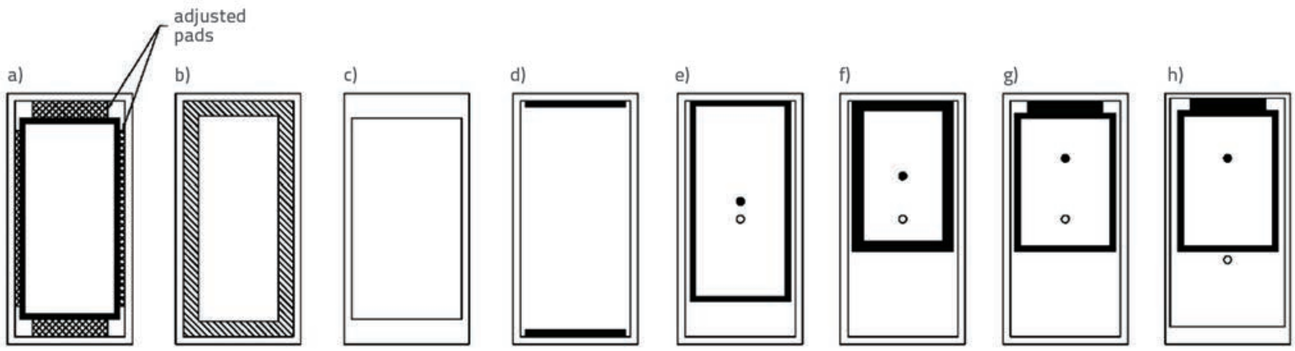


Figure 6. Analysed reinforcements

corrosions. The case (b) is similar solution with insertion of additional profile of aluminium alloy with no composite action. This solution as well exists in practice but these are always specially designed profiles which are not from standard assortment. The case (c) is a specially designed, stronger, profile aluminium alloy, which is also feasible but requires the manufacture of tools for extruding.

The case (d) is solution proposed by this paper with symmetrically arranged steel elements in idealised form. The cases (e) – (h) are given as an illustration of other solutions that were analytically examined and rejected.

The case (e) is solution with inserted steel tube from the standard assortment, assuming that controlled connecting is practically feasible only by one side. At this case it is obvious that contribution in relation to the case (a), as standard solution from practice with no composite action, is irrelevant. Previously this could have been expected because of small distances between centres of gravity of component parts of cross-sections, so positioning part of second moments of area contribute very little to the ideal cross-section total second moment of area.

To lessen the effect of the mentioned defect the following cases have been attempted: (f) where the position part of second moment of area in the total second moment of area of ideal cross-section is enlarged with intention, by moving centre of gravity of steel part of cross-section by adopting standard steel profile of lower height and thicker walls, (g) where there is additional moving of centre of gravity of steel part of cross-section done by welding a sheet at upper side of standard steel profile, and (h) where the same is done by moving, in opposite directions, the centres of gravity of the both profiles. At the last case, as in the case (c), the manufacturing of extruding tool is necessary.

Table 1. Cross-sections characteristics from the Figure 6

			(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Ideal cross section according to aluminium		A_i [cm²]	22,6	19,0	14,8	14,6	22,6	30,7	24,5	22,9
		I_i [cm⁴]	229,0	225,8	228,9	237,7	231,6	233,6	228,9	230,3
		$W_{i,el,min}$ [cm³]	45,8	45,2	45,8	47,6	42,6	37,5	36,0	38,1
		$W_{i,pl}$ [cm³]	63,8	58,4	54,6	55,2	63,9	72,3	65,2	63,0
		z_{max} [cm]	5,00	5,00	5,00	5,00	4,57	3,78	3,64	4,00
		z_{min} [cm]	5,00	5,00	5,00	5,00	5,43	6,22	6,36	6,00
		A_s/A_a				0,233	0,535	0,860	0,616	0,616
Components cross sections	Aluminium	A_a [cm²]	8,6	8,6		8,6	8,6	8,6	8,6	8,6
		I_a [cm⁴]	112,1	112,1		112,1	112,1	112,1	112,1	106,7
		$W_{a,el,min}$ [cm³]	22,4	22,4		22,4	22,4	22,4	22,4	18,7
		$W_{a,pl}$ [cm³]	27,8	27,8		27,8	27,8	27,8	27,8	24,6
	Steel (Aluminium)	A_s [cm²]	4,6	(10,4)		2,0	4,6	7,4	5,3	5,3
		I_s [cm⁴]	39,0	(113,7)		41,9	39,0	34,5	30,7	30,7
		$W_{s,el,min}$ [cm³]	9,7	(24,2)		8,9	9,7	11,5	8,1	8,1
		$W_{s,pl}$ [cm³]	10,8	(29,8)		9,1	10,8	14,7	11,3	11,3

The newly introduced tags are elastic and plastic section modulus of the ideal, aluminium and steel parts section: $W_{i,el}/W_{a,el}/W_{s,el}$ i $W_{i,pl}/W_{a,pl}/W_{s,pl}$

In all cases, and in accordance with expectations that bending deformation of the beam is a deciding characteristic, targeted characteristic of ideal cross-section was achievement of at least double second moment of area in relation to profile that is being reinforced. From the characteristics of cross-section at Figure 6 given in Table 1, is possible to see that connecting steel reinforcements as inserted profiles with basic profile of aluminium alloy cannot significantly rise aimed characteristics in relation to corresponding solutions without composite action. In examined cases the increase is about 15 %, which is for case (h) at figure 6 which is the most negative regarding feasibility. More than this is not possible to achieve even theoretically due to available space inside the basic profile of aluminium alloy. In addition, due to important values of ratio A_s/A_a and eccentricity of connection planes, important part of this contribution is annulled because of impact of temperature change. It can be concluded that improvement of standard solutions from practice, designed with no composite action, in a way that such solutions are with controlled composite action, is not the way to look for an improvement.

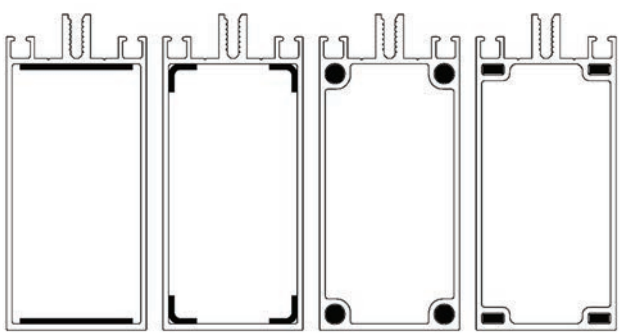


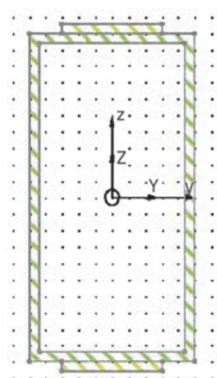
Figure 7. Some ideas for composite cross sections with bonded steel reinforcements

On the other hand, it can be shown that the optimal solution, by most criteria, is the proposed solution (d) of Figure 6. According to the criterion of quantity and price of the additional material this is obvious and from the Figure 6 itself and from Table 1. According to the criteria of the effect of temperature this is also advantageous because the ratio of A_s/A_a is the smallest, and connection is achieved centric, so the effects of temperature are reduced only to generated axial forces, or temperature does not affect the bending, which is expected to be competent criterion in analysed applications. The disadvantage of the proposed solution is certainly the work needed to achieve connection necessary for composite action. Bonding by structural adhesives is seen as a suitable system for connecting. Joining by self-drilled screws is also technically acceptable and according to current standards, or research shown in [15], it is sufficient to realize the connection at ~10-15 cm in length of the beam. In the analysed applications for aluminium façades, however, it is probably unacceptable that the head of screws are visible from the interior side. Bonding is also seen as suitable for the physical separation of steel and aluminium alloy which is favourable from the standpoint of eliminating contact corrosion. Also, the current standard for aluminium alloys [11] is one of the few standards which contain guidelines for the implementation of structural adhesives. Of course, it is needed to devise a way to carry out bonding at the inside of the tube-like base profile. From consultations with manufactures it can be concluded that this is not an insurmountable problem but it belongs more within the scope of patents and, of course, is a craft challenge. Some initial ideas are shown in Figure 7.

5. An example for the analysis and the experimental testing

As an example for the analysis and pilot experimental test on one sample for verification of analysis of behaviour, a modified case (d) of Figure 6 is chosen. The steel reinforcements are predicted for bonding at external side of aluminium alloy profile. This was resorted to due to accessibility for bonding and positioning of measuring tapes during testing and due to irrationality of dealing with technical aspects of bonding at interior side of basic profile at this phase of research. The cross-section of chosen case with basic geometric values, neglecting the thickness of the adhesive, is given at figure 8.

To simulate the most often encountered situation in practice when competent for the design is the deformation of beam, and for efficient exploitation of the profiles that are ordered in lengths of 6.0 m, the adopted span is 2.8 m. The static scheme is given at Figure 9 together with isometric insight of general arrangements of pilot sample, and the photograph of achieved failure upon the criteria of deformation from testing.



Ideal cross section according Aluminium

A_i = 14,04 cm²
I_i = 255,4 cm⁴
$W_{el,i}$ = 48,2 cm³
$W_{pl,i}$ = 55,6 cm³
z_{min} = 53,0 mm
z_{max} = 53,0 mm

Components cross section
Aluminium: [] 100x50x3

A_a = 8,64 cm²
I_a = 112,1 cm⁴
$W_{el,a}$ = 22,4 cm³
$W_{pl,a}$ = 27,8 cm³

Čelik: 2 ≠ 30x3
A_s = 1,8 cm²
I_s = 47,8 cm⁴
$W_{el,s}$ = 9,0 cm³
$W_{pl,s}$ = 9,2 cm³

Figure 8. Geometric characteristics of cross-section given as an example and for experimental testing

Used experimental example was made from material as available at market such as aluminium alloy *AW6060-T66* which upon [11], for thicknesses $t \leq 5$ mm, have 0,2 % proof strength $f_{a,y} = f_0 =$ 160 MPa, ultimate strength $f_{a,u} =$ 215 MPa and elongation at break of $\varepsilon_a =$ 8 % and steel S235 that, upon [14], have yield strength $f_{s,y} =$ 235 MPa, ultimate strength $f_{s,u} =$ 360 MPa i and elongation at break of ε_a=15 %. The example is designed such that local and global stability, shearing at the rib of the aluminium alloy tube and shearing in the adhesive layer, are not of significance, i.e. the estimation of exploitation upon these criteria is sufficiently small that in further discussion can be neglected. By this way the accent is put to the analysis of beam stiffness and cross-section resistance.

Bonding is done by two-components structure adhesive "Adesilex PG1" made by "MAPEI" following the manual at all points. Technical warranty of the adhesive declare the shear strength, which is the most important characteristic in designed examples here, as >35 MPa for temperatures up to 50 °C, i.e. as >25 MPa at temperature of 70 °C. Theoretical shear stress in the adhesive layer at expecting load at break in the sample is about 1.0MPa or <3 % of declared shear strength of adhesive. If the recommended safety factor for bonding joints of current regulations [11] **(γ_{Ma} = 3.0)** is taken into consideration, then theoretical shear stress at expecting loads of the sample is < 9 % of reduced shear strength of bonded layer declared by technical manual. However, bonded layer deserves special research attention anyway. But the sample for confirmation of theoretical model of behaviour of aluminium and steel composite beam is designed such that exploitation of adhesive layer is sufficiently small to allow be neglected and the adhesive seems convenient as the means of connection regarding condition it provides as close to ideal (continual connection joint) which is analysed in theoretical sense. The alternative was connection with self-drilling screws, but that would be discreet connection that deviates from theoretical assumptions as starting points in this paper.

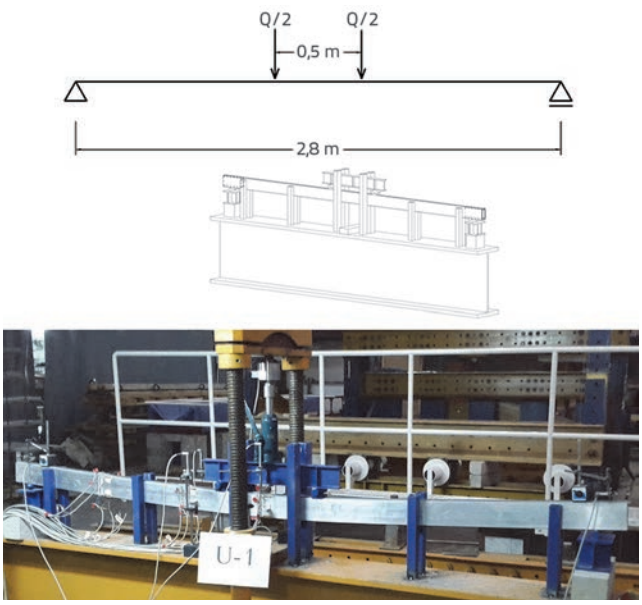


Figure 9. The static scheme of samples, isometrics of general arrangement of test and photo of achieved failure at deformation criteria

The confirmation of assumption that behaviour of bonded layer has no influence to the results of test has been gained by the measuring results of relative deformation of bonded parts at the beam's ends. These readings during measuring itself stayed below 1/100 part of millimetre, and difference between zero reading and reading after unloading is 1/1000 part of millimetre, which are the values at boundary of resolution of used instrument (0.01 mm) and below their declarative accuracy (0.03 mm), and also clear sign that shear strength of the adhesive layer was not critical at achieving the failure.

5.1. Analytical estimation of cross-section resistance

For practical applications it is necessary to determine the way of calculating determination of serviceability limit state (SLS) of composite beam, i.e. ultimate limit state (ULS) of cross section resistance of composite beam. For such purpose idealised adjacent stress-strain diagrams of component materials showed at Figure 10 have been used. In proportion are shown characteristic values and simplified forms of σ - ε diagram for applied aluminium alloy of basic profile and steel material of reinforcement are given in accordance to current regulations for related materials, [11, 14].

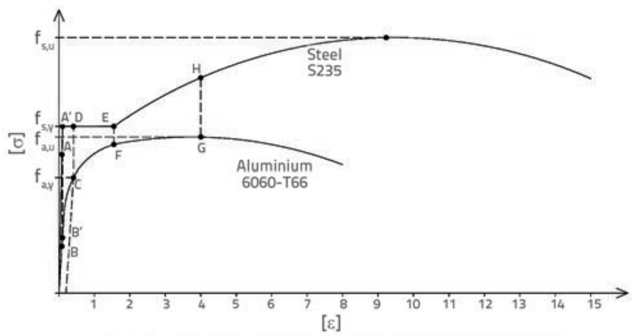


Figure 10. Adjacent σ - ε diagram of common fibres of composite cross section

Geometrical characteristics of idealized cross-section of composite beam can be used for calculating the serviceability limit state (SLS). In this way, for conventional permissible deformation of ***l/200* = 1.4 cm,** reaching SLS in the analysed case can be determined from the elementary terms of theory of structures where stresses states remain below the limit of proportionality of both materials. With above assumptions, serviceability limit state, for case under consideration, is reached at force of Q = 2 x 2,87 = 5,74 kN. For the purpose of comparison, the computationally obtained load on reaching the serviceability limit state, for the same level of allowable deformation in the case of independent profiles of aluminium alloys is 2.52 kN. This confirms that, the proposed reinforcement for targeted structural response, stiffness, or reaching the serviceability limit state (SLS), gains improvement by about 128 %. This improvement is in proportion to the second moment of area of idealized composite cross-section reduced to the characteristics of the aluminium alloy and the second moment of area of the independently observed of aluminium alloy profile

– Figure 8. In this, the stresses in the steel reach ~ 90 % of the steel yield strength and in the aluminium alloy reach ~ 40 % of the 0,2 % proof strength of the aluminium alloy.

In assessing the ultimate limit state (ULS) problem becomes more complex and, in general, it is not possible to see a way to do so, in a sufficiently precise manner, using the characteristics of an idealized composite cross-section. Looking at the steel and aluminium connection, with complete idealization of the same, it is clear that fibres of both materials in a connection plane, where are the maximum stress in aluminium alloys and about the maximum stress in the steel reinforcement, must have the same strain at all levels of the applied load. Likewise, distinctly different elongations at failure in two connected materials, which can be seen in the Figure 10, in combination with qualitatively different forms of σ - ε diagram for these two materials, clearly indicates the impossibility of failure by steel, i.e. the failure of composite cross-section must come at failure of basic profile of aluminium alloy. Next, the steel has a pronounced yield strength while the aluminium alloy does not, which is also evident in Figure 10, so this fact indicates that, at least in such adopted general arrangement of reinforcement, in steel it will come at least to the full plasticization of cross-section before failure occurs in aluminium alloy profile, i.e. failure of composite cross-section as a whole.

From the Figure 10 it could be seen that, at least for the analysed case and for common fibre of connected materials, reaching the serviceability limit state (SLS) can be expected at stresses that remain in the elastic field of steel (point A) and aluminium alloy (point B). Further increasing the load on reaching the yield strength stress will first come in steel (point A') whereby the stress in the aluminium alloy will achieve some level (point B') under 0,2 % proof strength. With further increasing load in the aluminium alloy is achieved the 0,2 % proof strength (Point C), while the steel comes to the full plasticity of cross-section and stress in the steel does not increase with the strain, point D. Finally, only merely theoretical, since unacceptably large deformation of the beam in the analysed general arrangement can be expected under these strains, further increasing the load exhausts the "plateau of plasticity" of steel (Point E) where the stress in aluminium surpassed 0,2 % proof strength but is still below the ultimate strength (point F). And finally, again purely theoretical because of the aforementioned reason, by further increasing the load, stress reaches tensile strength in aluminium alloys (point G) while the tension of the steel enters the zone post-plasticity "amplification" but does not reach the tensile strength of steel (point H), nor theoretically can reach it prior to fracture of the aluminium alloy since the strain at ultimate strength of steel is approximately twice the strain at ultimate strength of aluminium alloy. The current codes for steel [14] and aluminium [11] structures, however, do not take into account the post-plasticity behaviour of materials at the estimation of cross-section resistance, i.e. beam, unless the cases of net cross-section, which is not in the analysed cases, so the proposal for the calculation of the (ULS) composite cross-section remains on the plastic moment of resistance of steel part of cross-section, which is definitely on the safe side. An attempt to foresee analytically the growth of stresses in the composite cross-section for the typical inter-phases at Figure 10, are presented at Figure 11.

It should be kept in mind, however, that aluminium alloys are a wide range of materials and with the strongest alloys in combination with steel S235 diagrams analogous to the Figure 10 would have intersections, which can complicate applied way of the analysis. This problem, as needed, could simply be eliminated by application of the stronger steel, for example S355, while diagrams of the Figure 10 stay qualitatively in the same mutual relations even for the strongest aluminium alloys.

In the regulations and literature, where generally quoted, [7, 12, 13], as the method of analysis of combined (hybrid) or aluminium and steel composite, as possible method for estimations of resistance, the procedure at which each of component materials, i.e. corresponding profiles would be analysed for analogous influences in accordance with regulations valid for the said material is cited. It is sure that similar logic must be applied in the case of the estimation of analysed example of aluminium alloy and steel composite cross-section at analysis of ultimate limit state resistance (ULS) where, for now, the possibility to observe an idealised composite cross-section till the fracture with realistic taking into account the qualitatively and quantitatively essentially different σ - ε diagrams of two connected materials is simply not seen. For that reason the sum of capacities of components of cross-section upon materials is seen as convenient calculating model for composite cross-section resistance of beam, according to former analytics, i.e. diagrams of stresses at Figure 11. Namely, it is shown that steel component of the cross-section will reach full plasticity relatively early, while stresses in aluminium part are quite below its 0,2 % proof strength and full plasticity during further growth of load will stay constant, at least till reaching the capacity of aluminium part of composite cross-section.

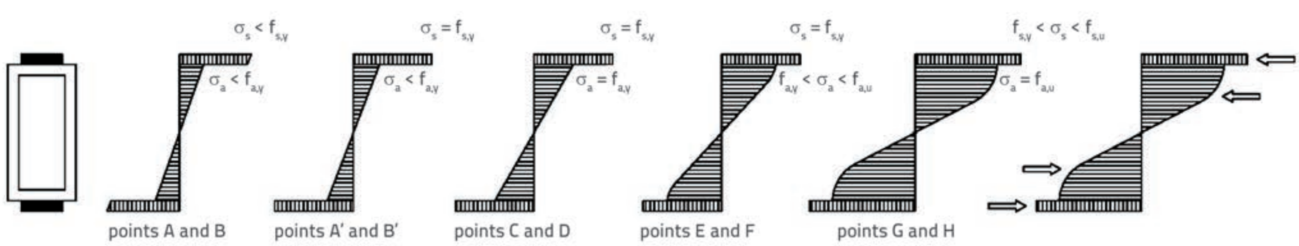


Figure 11. Axial stresses in cross-section for typical points of $\sigma - \varepsilon$ diagram of Figure 10

The moment of capacity of the aluminium alloy part can be determined according to the actual standard [11] and it is $M_{a,Rd}$ = 4,04 kNm (alloy of class A, cross-section of class 2, $\alpha = W_{pl}/W_{el}$ = 1,24, γ_{M1} = 1,10). When this moment of capacity transforms into load according to general arrangement of Figure 9, reaching of ultimate limit state (ULS) of aluminium profile can be expected at forces of Q_a = 2 x 3,51 = 7,02 kN. The moment of steel reinforcement capacity, when observed as independent cross-section, can be determined upon current standard [14] and it is $M_{s,Rd}$ = 2,16 kNm (steel S235, cross-section class 1, γ_{M0} = 1,0). Transformed into the force upon general arrangement from the Figure 9 the resistance moment is reached at force of Q_s = 2 x 1,88 = 3,76 kN. By this methodology total moment of resistance, i.e. applied force, at reaching ULS of composite cross-section can be estimated at M_{Rd}= (4,04+2,16) = 6,20 kNm, i.e. Q = 2 x (3,51+1,88) = 10,78 kN, which represents growth regarding the capacity of basic aluminium profile that is reinforced by 54 %.

The following analysis can be conducted in regard to the influences of temperature change to the cross-section resistance i.e. to the ultimate limit state (ULS). Temperature change of, for example ΔT_u = ±30 °C, at extreme situations in composite beam of analysed example, upon the equation (4), would generate the force $\pm N_a = \pm N_s$ =7,5 kN, i.e. stresses in steel of $\pm\sigma_{s,\Delta Tu}$ = 41,7 MPa, which is ~17.7 % of steel yield strength, and of $\pm\sigma_{a,\Delta Tu}$ = 8,9 MPa in aluminium alloy, which is ~5.6 % of 0,2 % proof strength of aluminium alloy. With adopted calculation assumptions on capacity of composite cross-section, the influence of temperature change can, for determination of cross-section resistance, be taken into account simplified, by the way of introducing reduced yield strength of steel, $f_{sy,red}$, i.e. reduced 0,2 % proof strength of aluminium alloy, $f_{ay,red}$, by which corresponding, known in advance, stress range is simply left reserved for the influence of temperature change. At formerly described way gains for the steel $f_{sy,red}$ = 235-41,7 = 193,3 MPa, i.e. for the aluminium alloy $f_{ay,red}$= 160-8,9 = 151,1 MPa, so reduced moment of capacity of coupled cross-section, i.e. corresponding reduced force upon disposition at the Figure 9 become $M_{Rd,red}$= (3,81+1,78) = 5,59 kNm, i.e. Q_{red}= 2 x (3,31+1,55) = 9,72 kN. Previous analysis shows that influence of adopted, truly possible, temperature change reduces cross-section resistance for about ~10 %, i.e. final improvement of resistance, which in analysed applications is most often not competent, is respectful ~38.5 %, while improvement of stiffness as targeted characteristic for improvement of basic profile stays unchanged (128 %). In real situations the temperature change impact to stiffness and resistance of composite cross-section is lower since, at combination of action, the possibility of several variable actions applying at the same time is taken into consideration. Upon current standard [16], for the simultaneous effects of dominant variable action, in analysed situations that is the wind, in combination with additional variable action, in analysed situations that is temperature change, additional variable action is reduced with factor for combination ψ_0=0,6.

It can be shown that, in the case where bearing resistance is important, similar analysis, by application of the steel S355, with same ratio in stiffness in relation to variation with steel S235, would result in contribution to capacity in regard to basic profile which is strengthened with no influence of temperature changes, for ~80.9 % and with considering the influences of temperature change capacity stays for ~65.8 % higher in relation to basic profile that is strengthened. For analysed case in both variants with S235 and S355, it is possible to say that capacity is still not competent for design, since, in regard to partial factor for action according to [16], load resistance becomes competent only if the effects of the design actions during reaching ULS below 140-150 % of design actions during reaching SLS.

6. Pilot test results

General arrangement of a pilot experimental test on one sample for verification analysis of behaviour is shown in Figure 9. Testing of materials for pilot test was not done already but all data are taken from certificates of materials. In the case of aluminium alloy data for 0,2 % proof strength and elongation at break (205 Mpa and 11.7 % from certificates compared to 160 MPa and 8 % from [11]), differ substantially, and while the tensile strength (225 Mpa from certificates compared to 215 MPa from [11]) variations are lower. In the case of steel materials, declarative S235, certificate has been given all the relevant values within 5 % close to the stronger steel S275 according to [14].

For the pilot test measuring the strains was done only in the middle of cross-section, and mere examination at this stage of the research, was done at room temperature or at the temperature of bonding.

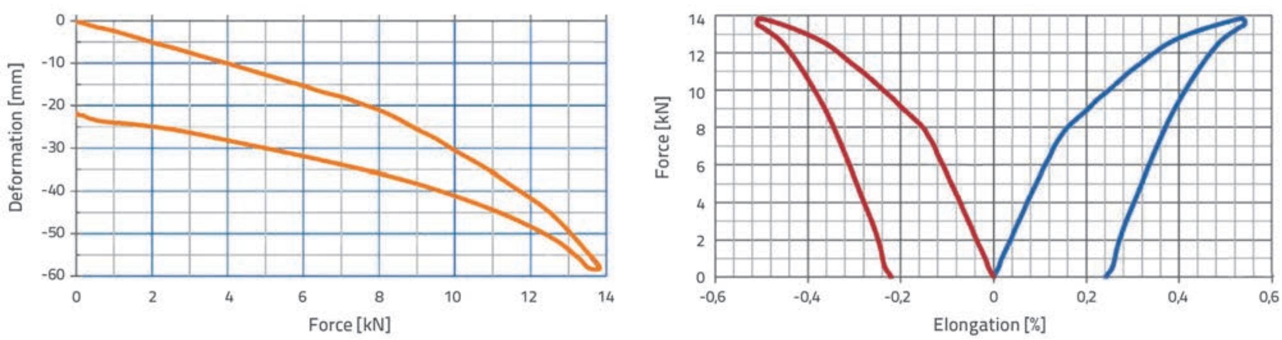


Figure 12. Diagrams on force-deformation and force-strain proof testing of composite beam

Diagrams describing the force–deformation of beam and force-strain of common fibres of connected materials in a conducted pilot examination of test sample, together with the relief phase, are shown in Figure 12. From the diagram it can be clearly seen three zones of behaviour of composite beam where the transitions from one to another zone can be linked to specific points in the Figure 10, reaching the yield strength in steel, i.e. reaching the 0,2 % proof strength at aluminium alloys.

The results show expected good folding of diagrams presenting the force-displacement in the field of elastic behaviour with computational study values. Specifically, the predetermined load at the achievement of SLS, 5.74 kN, by an experiment was measured as force of 5.80 kN. The difference between estimated and actual values amounting to ~ 1 % can be, with applied idealization first of all neglecting of the adhesive layer, considered as very good. For this phase of loads measured stresses, or appropriate strain, are also in good agreement. The measured values of stress, i.e. corresponding strain with steel are ~ 5 % higher than a computational, analogue values measured at the aluminium alloy ~ 6 % higher than the corresponding values obtained analytically.

General arrangement applied during proof testing did not allow reaching classical failure or ultimate limit state resistance (ULS) since before it came to utilization of space allocated for the deformation of the beam aligned with stroke of applied press. It can, however, say that the failure is achieved according to the criterion of deformation which, according to [17] "SRPS U.M1.047: 1987 – Testing building constructions by the pilot load and test to fracture" which is under the changed name still valid standard in most of the countries that emerged from the former SFRJ, defines with L/50 (5.6 cm in the case of applied general arrangement of the test sample). This condition is reached with the force of 13,36 kN. The predicted space for the deflection allowed increase of the force to 13,83 kN, while the decline of the ability to accept additional load is registered, so it is estimated that classical failure due to exhaustion of material are very close.

In support of this hypothesis are diagrams of unloading shown in Figure 12, which represent a significant plastic deformation. The resistance bending moment and the level of the applied load at achieving the ultimate limit state, analytically determined as already described, but with the characteristics of the material from attest documentation amounts $\boldsymbol{M_{Rd,exp}}$ **= (5,17+2,53) = 7,70 kNm,** or Q_{exp} = 2 x (4,50+2,20) = 13,40 kN. The intensity of the load at ULS obtained analytically is slightly smaller, within ~ 3 % of the intensity measured during tests.

Measured strain at maximum of achieved load indicate strain in common fibre of aluminium alloy and steel of about 0.7 %, which clearly indicates that the steel is substantially entered the "plateau of plasticity", so the stress in the steel is around the limit of yield strength, i.e. 275 MPa. Aluminium alloys in the achieved elongation for mechanical properties from certificate of the materials, and according to models offered σ - ε behaviour of the aluminium alloys in Annex E of the applicable standard [11], that is predominantly derived from the Ramberg-Osgood Law modified in a way that is shown in [8, 9], and for which the tables of mechanical characteristics of the current standards [11] supplies the necessary exponent "$\boldsymbol{n_p}$", resulting in tension of ~ 211 MPa, which is the stress at the one third of range between the 0,2 % proof strength and ultimate strength of aluminium alloy from the attest of materials.

The examination of the test sample is conducted at the room temperature, i.e. the temperature of bonding, so the results are without effect that connecting of materials with different coefficients of thermal expansion produces by the change of temperature. Good comply of the results of the pilot experimental test with suggested model of the estimation initiated the program of detailed research, which is in progress, and where an examination with temperature changes is planned too.

7. Conclusions

Engineering curiosity, encouraged by the fact that combining of aluminium and steel is widely used in other engineering areas, initiated the research on possibilities for combining aluminium alloys and steel in the construction industry as an improvement of ways, commonly used in practice, of strengthening the beams of aluminium alloy for façade systems. The initial results of the study, at which the pilot experimental testing on one sample was conducted, showed that, by combining of aluminium alloys and steels with composite action, balanced beams can be achieved whose estimations on stiffness and load capacity can be relatively simple.

Special attention, from a theoretical point of view, is dedicated to the fact that the connection is made between two materials with different thermal expansion coefficients and qualitatively different σ - ε diagrams. Original parametric analysis showed that the different coefficients of thermal expansion of used materials are not an obstacle to rational applications in the construction industry. It is demonstrated analytically that disadvantages of combining of materials with different coefficients of thermal expansion do not prevent overall positive results, especially in situations that have initiated research, i.e. when deformation is the dominant request for design. The research, at this stage, does not deal with connection itself, the stability of composite beam or other aspects that also require analysis before practical applications, but remains on the analytical model of behaviour. The calculation methods to determine the stiffness of composite beam and resistance of composite cross section are proposed and are generally confirmed by pilot testing on a one sample. The encouraging results of the research, presented in this paper, have initiated a detailed research program whose implementation is in progress.

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