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Review paper

Aluminium members in composite structures – a review

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Abstract: This paper presents a review of composite structures in which aluminium alloys are used. Current trends in the research of composite structures with aluminium girders and their possible applications in structural engineering were shown. In the presented solutions, advantageous properties of aluminium alloys were exploited, such as high strength-to-weight ratio, corrosion resistance and recyclability. The authors demonstrated the structural behaviour of aluminium-concrete and aluminium-timber composite beams based on their own tests as well as investigations presented in the literature. Furthermore, aluminium-concrete composite columns, a composite mullion made of an aluminium alloy and timber, and a military bridge consisting of aluminium truss components, a stay-in-place-form, reinforcement and concrete were presented. In addition to the description of the structural elements, the main conclusions from their experimental, theoretical and numerical analyses were also demonstrated in this paper. The connection of aluminium girders with concrete or timber slabs provided for the increase of the load-bearing capacity and stiffness, and it eliminated the problem of local buckling in girder flanges and lateral-torsional buckling of girders in the analysed solutions.

Keywords: aluminium alloys, aluminium-concrete composite beams, aluminium-timber composite beams, concrete-filled aluminium tubes, engineered wood products

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1. Introduction

Aluminium alloys have been available since the end of the 19^{th} century [1]. For this reason, their application in civil engineering is a relatively recent practice. They have many advantageous properties, e.g., they have a high strength-to-weight ratio [2], they are corrosion resistant [3] and recyclable [4], and the elements made of them are easy to extrude, which makes it possible to design any cross-section [5]. Extruded sections are not the only possibility. Recently, cold-rolled aluminium members have been fabricated using a roll-forming process in Australia [6]. Aluminium alloys also have some disadvantages. The first one is the high price of aluminium alloys compared to steel. However, the difference between the prices of aluminium alloys and steel is gradually decreasing [7]. Furthermore, the lack of the need for periodic painting of aluminium members results in lower maintenance costs. The second disadvantage is the low fire resistance of aluminium members. However, it may be increased by using passive fire protection with thermal insulation materials presented in [8]. The third disadvantage is the modulus of elasticity of aluminium alloys, which is three times lower than that of steel. The deflections of aluminium beams are larger than of steel beams with the same cross-sections. For this reason, an aluminium beam should be higher than a steel one. However, the weight of the aluminium beam does not necessarily have to be greater, because aluminium alloys are three times lighter than steel. The first applications of aluminium alloys in civil engineering were the cladding of the dome of the San Gioacchino church in Rome (1897) [9] and the aluminium span of the Grasse River Bridge erected in 1946 [10]. The contemporary examples of the applications of aluminium alloys for structural members in civil engineering are presented below:

- lightweight bridge decks made of aluminium alloys used for replacing or reconstructing deteriorated bridge decks [11, 12];
- elevations, temporary buildings and warehouses [13];
- the cladding of platform shelter roofs [13], structural roofing [14] and roof panels [15];
- bridges [16];
- domes, silos [1], tanks in sewage treatment plants [17];
- towers [2];
- off-shore structures and helidecks [18];
- strengthening of reinforced concrete beams [19–21];
- anchoring cross laminated timber shear walls [22].

As shown above, aluminium members are widely used in civil engineering. However, the use of aluminium members in composite structures is not popular due to the lack of standards, such as Eurocode 4 for steel-concrete composite structures [23, 24]. Composite beams usually consist of slabs and girders made of different materials. They are permanently joined using shear connectors, which makes them more efficient [25–27]. Beams may be fully composite or partially composite (when the number of shear connectors is insufficient to ensure full composite action) [28]. Slip may occur between the girder flange and the slab [29]. For this reason shear connections may be rigid or flexible [30]. Flexible connections exhibit non-negligible slip between the girder flange and the slab, whereas slipping in rigid connections is so low that its impact on the stiffness and the load-bearing capacity of a composite beam is negligible. The slip may also occur in partially composite beams.

Composite structures with aluminium members are still the object of many studies. In paper [31], the stiffness of a steel-concrete composite beam, an aluminium-concrete composite beam, a steel-timber composite beam and an aluminium-timber composite beam was compared. The beams were fully composite and they had the same geometric dimensions. For each composite beam, the connection of metal girders with concrete or timber slabs provided for greater stiffness. The steel-concrete composite beam demonstrated the highest stiffness among the analysed composite beams, followed by the steel-timber composite beam and the aluminium-concrete composite beam. The aluminium-timber composite beam demonstrated the lowest stiffness among the analysed composite beams. In paper [32], the load bearing capacity of beams made of S235 steel, 1.4571 stainless steel or AW-6061 T6 aluminium alloy was analysed before and after they had been joined with concrete slabs. The load-bearing capacity of the aluminium girder, the steel girder and the stainless steel girder increased 7.7, 4.7 and 4.5 times, respectively, after they had been joined with concrete slabs. In paper [33], composite beams with aluminium girders were described. In this paper, extended information on the solutions presented in [33] and additional examples of composite structures with aluminium members are described.

2. Aluminium-concrete composite structures

Aluminium members can be connected with concrete members. An aluminium truss may be connected with a concrete slab to create light-weight military bridges. A prototype of the military bridge consists of aluminium truss support components, a pultruded glass fibre reinforced polymer stay-in-place-form, reinforcement and concrete made in field conditions [34–36].

Aluminium tubes may be filled with concrete to create aluminium-concrete composite columns. The use of concrete inside aluminium tubes has two major benefits, i.e., it improves the capacity and the fire resistance of columns [37]. The use of aluminium tubes outside of the concrete core also has two major advantages, i.e., aluminium tubes act as stay-in-place formwork and they promote the confinement effect [38] (Fig. 1).

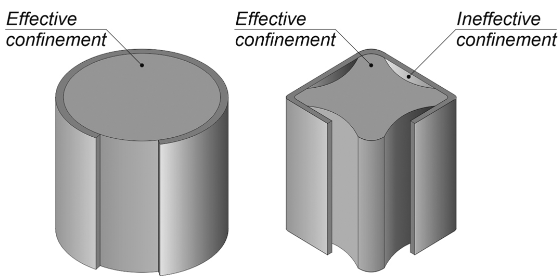


Fig. 1. Confinement effect in aluminium-concrete columns [38]

Furthermore, aluminium-concrete composite columns may have higher ductility than their aluminium counterparts, because they contain a greater amount of material and because of the confinement effect. This regularity was observed in the laboratory tests of concrete-filled steel tubular columns conducted by Grzeszykowski [39].

Aluminium tubes may have square, rectangular or circular hollow sections (Fig. 2).

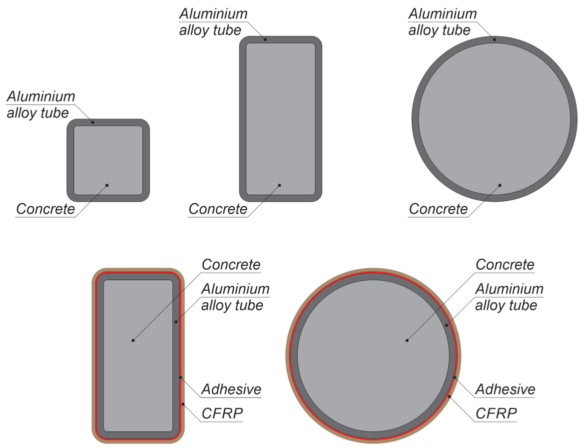


Fig. 2. Aluminium-concrete columns [37, 38, 41, 42, 46]

The square or rectangular cross-sections demonstrate some loss of the confinement effect compared to circular cross-sections [40]. Furthermore, square or rectangular aluminium tubes may split near their corners and cause the failure of columns [41], whereas the splitting of the circular aluminium tubes is unlikely [42].

The confinement effect depends on:

– the cross-section type (the confining effect is stronger in a circular cross-section than in a rectangular cross-section) [40, 43],
– concrete strength (the confining effect becoming worse with the increasing of concrete strength) [44, 45],
– generalized outer diameter-to-thickness ratio α (the confining effect becoming worse with the increasing of the ratio) [45]:

$$\alpha = \frac{D}{t}\frac{f_y}{E}, \tag{2.1}$$

where: D – the outer diameter of the tube, t – the thickness of the tube, f_y – the yield strength of tube material, E – the modulus of elasticity of tube material.

The question is does the intensity of the confinement effect depends on tube material (steel, aluminium alloy)? To compare the intensity of the confinement effect in concrete-filled steel tubular columns with the one in concrete-filled aluminium tubular columns the laboratory tests on specimens having identical geometry and made of the same concrete should be conducted. In this paper, the authors compared generalized outer diameter-to-thickness ratio α of steel and aluminium tubes (Table 1).

Table 1. Generalized outer diameter-to-thickness ratio α of steel and aluminium tubes

Tube material	α [–]	α ($\beta = 20$) [–]	α ($\beta = 100$) [–]
S235	$0.0011\beta^*$	0.022 $(1)^{\#}$	0.11 (5)
S355	0.0017β	0.034 (1)	0.17 (5)
AW-6060 T6	0.0020β	0.040 (1)	0.20 (5)
AW-6082 T6	0.0037β	0.074 (3)	0.37 (6)

* $\beta = D/t$,
$^{\#}$ (n) – the category of the cross-section [45].

According to [45], the tube cross-section were divided into six categories based on the ratio α. Depending on the ratio α and concrete strength, the ductility and failure modes of concrete cores (splitting failure of the concrete core or shear and sliding failure) in the post-buckling stage may be evaluated (Table 2).

Table 2. Failure modes and ductility of the concrete core in the post-buckling stage [45]

Cross-section category	Concrete strength				
	$\leq$ 30 MPa	30–40 MPa	40–50 MPa	50–60 MPa	> 60 MPa
1	A*, I$^{\#}$	B, I	B, I	B, I	B, II
2	A, I	B, I	B, I	B, II	B, II
3	A, I	B, I	B, I	B, II	B, III
4	B, I	B, I	B, II$^{\wedge}$	B, II	B, III
5	B, I	B, I	B, III$^{\&}$	B, III	B, III

* the failure mode of the concrete core (A – splitting failure of the concrete core, B – shear and sliding failure),
$^{\#}$ I – an unlimited growth trend of the strength of the concrete core [45], the highest ductility and confining effect [39],
$^{\wedge}$ II – a considerable compressive strength for the concrete core but with obvious damages [45], significant ductility and confining effect [39],
$^{\&}$ III – the serious damages of concrete core, the residual capacity of circular concrete-filled tube columns is not available [45], the lowest ductility and confining effect [39]

One can observe from Table 1 that the use of aluminium alloy instead of steel provide to higher value of ratio α and may change the cross-section category (compare S235 grade steel and AW-6082 T6 aluminium alloy). The intensity of the confinement effect decreasing with concrete strength and cross-section category rising. For this reason, the intensity of the confinement effect depends slightly on tube material (steel or aluminium alloy).

Concrete-filled aluminium tubes may be reinforced at their exterior walls with carbon fibre-reinforced polymer to delay the outward local buckling of aluminium tubes [46]. The analysed aluminium-concrete composite columns did not have connectors at the interface of aluminium alloy and concrete because, similarly to steel-concrete composite columns subjected to compression [47], the connection between these two materials was achieved through the natural bond between them. However, shear connectors should be applied when the design value of longitudinal shear stress exceeds the design shear strength presented in Eurocode 4 [23]. According to Eurocode 4 [23], the design shear strength depends only on the cross-section type, whereas Szadkowska and Szmigiera [48] demonstrated that the thickness of the tube wall, the cross-section geometry and the strength class of concrete also have an impact on the design shear strength. The presented research papers on aluminium-concrete composite columns do not focus on the compaction method of concrete. In the case of concrete-filled aluminium tubes, vibrated or self-compacting concrete may be used. Self-compacting concrete may overcome some technological difficulties in the production process which are typical of vibrated concrete. However, Szmigiera and Woyciechowski demonstrated that for steel-concrete composite columns the bond between vibrated concrete and steel is stronger than the bond between self-compacting concrete and steel [49].

After being connected with concrete slabs, aluminium girders create aluminium-concrete composite beams. The applications of these structures are demonstrated in [50]. Due to aluminium alloy corrosion resistance, they may be used in bridges, foot bridges, marine structures, swimming pools, sewage treatment plants, and storage warehouses for storing chemicals or fertilizers. One other application was presented in [7], i.e., aluminium truss girders and lightweight reinforced concrete may be used for structural restoration and replacing an old deck in a bridge. An example of this solution is the retrofitting of the Groslee bridge in France. Due to aluminium alloy lightness, aluminium-concrete composite beams may be used for structures in inaccessible places. Aluminium girders may be carried by a helicopter to places which are difficult to access. Due to lower shrinkage stresses in aluminium-concrete composite beams than in corresponding steel-concrete composite beams [51], aluminium-concrete composite beams were suggested to be used as structural members in ceilings. However, in this application aluminium girders should be fire protected because of their low fire resistance [52,53]. Fire protective boards, horizontal membranes and sprays are recommended for steel-concrete composite structures [54] and steel structures [55]. The use of fire protective materials may increase the fire resistance of aluminium-concrete composite beams. However, the effectiveness of the above-mentioned fire protective boards, membranes and sprays in case of aluminium-concrete composite beams has never been tested in fire.

The behaviour of aluminium-concrete composite beams was analysed in several laboratory tests. Two aluminium-concrete composite beams with channel shear connectors subjected to bending were tested by Stonehewer [56] (Table 3). Based on the bending tests, the author suggested that the transformed section theory may be used to determine the stresses and strains in fully composite aluminium-concrete beams. Bolts as shear connectors were used in two aluminium-concrete composite beams subjected to bending tested by Bruzzese, Cappelli and Mazzolani [57] (Table 3). Mandara and Mazzolani [58] suggested that the stress block method may lead to overestimating the load-bearing capacity of the composite beams with aluminium girders because some aluminium alloys may not be ductile enough. The authors presented a method for designing this type of composite beams taking into account the limit values of strains. However, many of currently used aluminium alloys have good ductility, e.g., in the tests presented by Siwowski [59], the 5083 aluminium alloy had an elongation of 30%.

Siwowski [59] also used bolts as shear connectors in his tests on an aluminium-lightweight concrete composite beam (Table 3). The reinforced concrete slab in the beam was made of lightweight concrete with Lytag lightweight aggregate, while the girder was made of aluminium alloy (Table 3). The replacement of the steel girder with the aluminium girder and of the concrete slab with the lightweight concrete slab provided for a significant weight reduction.

Polus and Szumigała demonstrated an aluminium-concrete composite beam, in which a concrete slab is poured into profiled steel sheeting [60, 61] (Table 3). Concrete slabs with profiled steel sheeting contain a lower amount of concrete than solid slabs. The sheeting is a stay-in-place formwork and a safe working platform. When it is thick enough, it may stabilise the upper flanges of the girders during construction. Furthermore, profiled steel sheeting can reduce high temperature concrete spalling [54]. It should be galvanised to limit the corrosion of the aluminium alloy in contact with steel. Polus and Szumigała used patented dowel-bolt connectors as shear connectors [60, 61]. The connectors are demountable to allow the dismantling of a composite beam at the end of its structural life. Thanks to this functionality, aluminium-concrete composite beams fulfill the circular economy concept of sustainable construction. Civil engineering solutions should be easily deconstructed at the end of the service life of a building, so that the structural materials could be reused or recycled [62]. Furthermore, dowel-bolt connectors make it possible to achieve composite action without welding, whereas the commonly used headed studs are welded to the girder flange. In case of aluminium girders, welding may create heat affected zones and reduce the yield and the ultimate strength of aluminium alloys. Moreover, dowel-bolt connectors may be used in composite beams with profiled steel sheeting, whereas the most commonly used continuous connectors – composite dowels – are not used in composite beams with profiled steel sheeting [63]. However, composite beams with profiled steel sheeting and composite dowels as shear connectors have recently been analysed in [64]. Demountable dowel-bolt shear connectors were used in connections of four aluminium-concrete composite beams and four push-out specimens [61]. The connectors were installed in a predrilled flange of an aluminium girder and embedded in the concrete ribs of a slab. The connection consisted of the demountable dowel-bolt shear connector, the concrete which filled the rib and surrounded the connector, and the nuts which fastened the connector to the flange of the aluminium girder (Fig. 3).

The demountable dowel-bolt shear connectors were only placed in the ribs of the profiled steel sheeting. For this reason, the beams were with partial interaction and the degree of the shear connection was equal to 0.79. The load-bearing capacity of the unrestrained aluminium girders increased 5.2 times after they had been connected with the concrete slabs using the demountable dowel-bolt shear connectors (Table 4).

When the calculation procedure for steel-concrete composite beams with partial shear interaction presented in [65] was used, the load-bearing capacity of the aluminium-concrete composite beams was only 5% higher than the value obtained from the tests (Table 4). The

Table 3. Aluminium-concrete composite beams tested by researchers [56, 57, 59–61]

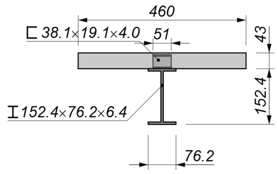
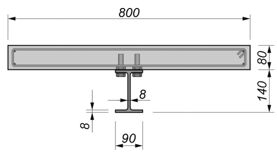
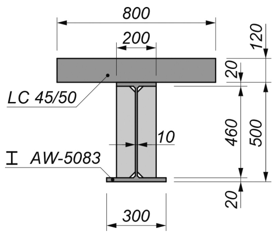
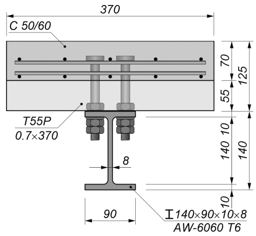
Test authors	Cross-section	
Stonehewer [56]		
	Girder	Height = 152.4 mm, magnesium-silicon aluminium alloy ($f_{0.2}$ = 275.79 MPa, f_u = 303.37 MPa)
	Slab	Thickness = 43 mm, solid, concrete (long beam: f_c = 22.34 MPa, short beam: f_c = 26.89 MPa)
	Connectors	Channel shear connectors
	Number of beams	2
Bruzzese, Cappelli and Mazzolani [57]		
	Girder	Height = 140 mm, aluminium alloy (beam 1: $f_{0.2}$ = 339.9 MPa, f_u = 394.9 MPa; beam 2: $f_{0.2}$ = 352.3 MPa, f_u = 410.5 MPa)
	Slab	Thickness = 80 mm, solid, concrete (f_c = 43.3 MPa – beam 1, f_c = 55.7 MPa – beam 2)
	Connectors	Bolts
	Number of beams	2
Siwowski [59]		
	Girder	Height = 500 mm, 5083 aluminium alloy ($f_{0.2}$ = 136 MPa, f_u = 286 MPa)
	Slab	Thickness = 120 mm, lightweight concrete (f_c = 52.3 MPa), solid
	Connectors	Galvanised steel bolts
	Number of beams	1

Table 3 [cont.]

<table>
<tr><th>Test authors</th><th colspan="2">Cross-section</th></tr>
<tr><td rowspan="5">Polus and Szumigała [60, 61]</td><td colspan="2">
</td></tr>
<tr><td>Girder</td><td>Height = 140 mm, AW-6060 T6 aluminium alloy ($f_{0.2}$ = 153.26 MPa, f_u = 207.68 MPa)</td></tr>
<tr><td>Slab</td><td>Thickness = 125 mm, with profiled steel sheeting, concrete (f_c = 61.82 MPa)</td></tr>
<tr><td>Connectors</td><td>Patented dowel-bolt connectors</td></tr>
<tr><td>Number of beams</td><td>4</td></tr>
</table>

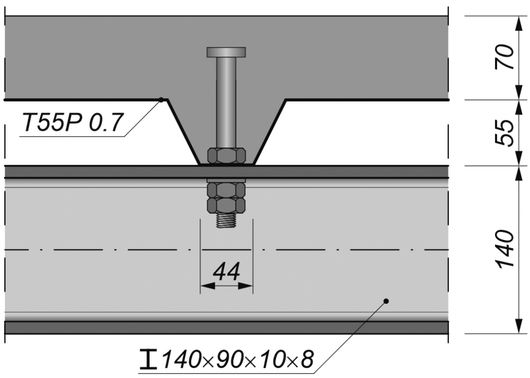


Fig. 3. Connection with a demountable dowel-bolt shear connector used in aluminium-concrete composite beams with profiled steel sheeting [61]

calculation procedure for steel-concrete composite beams with partial shear interaction was successfully used for calculating the load-bearing capacity of aluminium-concrete composite beams with profiled steel sheeting and demountable shear connectors. The behaviour of the connections with demountable dowel-bolt shear connectors was characterised in laboratory push-out tests. The stiffness of the analysed connections was relatively low (the connection slip modulus $k_{0.4}$ = 5.9 ±1.8 kN/mm) because of the clearance between the connector and the hole in the aluminium girder flange [61]. What is more, the connectors were non-preloaded. The tested connections were brittle and they showed signs of rib-shearing failure because relatively narrow ribs (44 mm) were used. The behaviour of

Table 4. Load-bearing capacities of the analysed beams [60, 61, 87, 88]

Test authors	Theoretical bending resistance of the unrestrained aluminium beam [kN·m]	Theoretical bending resistance of the restrained aluminium beam [kN·m]	Theoretical bending resistance of the composite beam [kN·m]	Bending resistance of the composite beam from the tests [kN·m]
Polus and Szumigała [60, 61]	14.0	22.3	75.5	72.2
Chybiński and Polus [87]	10.0	18.3	58.4	62.8
Chybiński and Polus [88]	10.0	18.3	64.5	69.9

the aluminium-concrete composite beams with profiled steel sheeting and dowel-bolt shear connectors was investigated in bending tests [61]. Similarly to the connections tested in the push-out tests, the analysed composite beams showed signs of rib-shearing failure, which is a brittle mode of longitudinal shear failure. The ductility and the stiffness of the connection should be increased during further research on connections using demountable dowel-bolt shear connectors in aluminium-concrete composite beams with profiled steel sheeting. To increase the stiffness and the ductility of the connections in aluminium-concrete composite beams, the solutions demonstrated to be effective for steel-concrete composite beams may be applied and tested. For example, Patrick recommended using waveform reinforcement to prevent rib-shearing failure [66]. Ernst et al. demonstrated that waveform reinforcement used together with steel wire spiralled around shear connectors could reduce the effects of the concrete-related failure modes of shear connections and increase their ductility [67]. Kozma et al. showed that the pre-tensioning of demountable shear connectors increased the initial stiffness of connections [68]. Pavlović et al. [69] demonstrated that the reduction of connector-to-hole clearances could increase the stiffness of shear connections.

The behaviour of aluminium-concrete composite beams was also evaluated in numerical analyses. The finite element models of the aluminium-concrete composite beam with demountable dowel-bolt shear connectors [61], bolted connections [70] or channel shear connectors [71] were developed and verified against the experimental results. The main conclusions from the numerical analyses of aluminium-concrete composite beams are as follows:

- In the numerical models of the aluminium-concrete composite beams with partial shear interaction, the shear connections can be modelled using zero-length springs, the load-slip behaviour of which had been previously obtained in laboratory push-out tests or from theoretical analyses. Discrete shear connections take into account the slip between aluminium girders and concrete slabs.
- In the numerical models of the fully composite beams with rigid connections, shear connectors may be modelled as beams fixed to the girder flange and embedded in the concrete slab. The second option is to use the tie function to model the connection between the slabs and the girders.

3. Aluminium-timber composite structures

Aluminium structural elements may be connected with timber elements to create aluminium-timber composite structures. Jiao et al. [72] developed a vertical aluminium-timber composite member which could be used in façades. Due to the fact that aluminium alloy is a highly heat-conductive material, the authors recommended using a composite mullion made not only of aluminium alloy but also of timber, to improve the thermal performance of façade systems.

Recently conducted research has shown that significant benefits are to be gained by joining aluminium girders and timber slabs. The application of aluminium alloy and timber in composite floors can significantly reduce their self-weight. The lightness of aluminium-timber composite beams may speed up the construction process and provide for cost reduction [73]. Timber is a fully renewable material and has a high strength-to-weight ratio [74]. The limitations of sawn timber were overcome when engineered wood products, such as glued-laminated timber, cross-laminated timber, plywood or laminated veneer lumber, had been manufactured [75]. Aluminium-timber composite beams also have some disadvantages. Thermal stresses should be taken into account when attaching aluminium girders to LVL slabs [76], because the thermal expansion coefficient for aluminium alloy (24×10^{-6} 1/$\circ$C [77]) is different from the one for LVL (8×10^{-6} 1/$\circ$C [78]). Thermal effects may be reduced in insulated and heated buildings, where the temperature change may be insignificant. The fire resistance of aluminium-timber composite beams is relatively low due to the low fire resistance of aluminium girders. The use of fire protective materials may increase the fire resistance of aluminium-timber composite beams. Aluminium girders may be partially or fully encased by LVL elements in a similar way to the steel girders demonstrated in [79].

Saleh and Jasin [80–82] used slabs made of plywood. Plywood slabs were connected with aluminium girders using self-tapping, self-drilling screws and an adhesive epoxy material (Table 5).

If the adhesive epoxy material had been used as the only form of shear connection, the slab could have separated from the girder at the ultimate load, as observed in the tests of steel-concrete composite beams conducted by [83]. The cooperation of the plywood slab and the aluminium girder eliminated the problem of local buckling in aluminium girders [80–82]. The investigated composite beams had a relatively low end slip (below 0.1 mm). For this reason, the analysed connections provided full interaction between the aluminium girders and the plywood slabs. The load-bearing capacity of the aluminium girders increased 1.18–1.56 times after they had been connected with the plywood slabs. In addition to plywood, a slab may also be made of cross-laminated timber (CLT) or laminated veneer lumber (LVL). The strength parameters of LVL were evaluated and discussed in article [84]. The characteristic resistance of the LVL from the tests was higher than the characteristic resistance declared by the manufacturer. The applications of LVL in civil engineering were demonstrated in articles [85, 86]. LVL slabs and beams are used in framed construction. However, LVL may also be used in steel-timber, aluminium-timber or timber-concrete composite structures. Chybiński and Polus [87–89] connected LVL slabs with aluminium girders using screws or bolts as shear connectors (Table 5). Each girder in the tests conducted by the authors [87–89] was made of the same aluminium alloy and had the same cross-section. When failure load was applied to the aluminium-timber composite beams tested by Chybiński and Polus [87, 88], the veneers delaminated in the parts of the LVL slabs subjected to tension, and cambered and crashed in the parts of the LVL slabs subjected to compression.

Table 5. Aluminium-concrete composite beams tested by researchers [80–82, 87, 88]

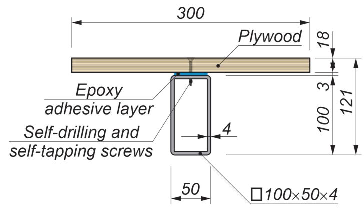
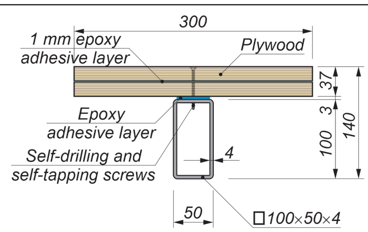
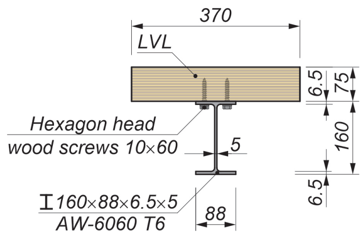
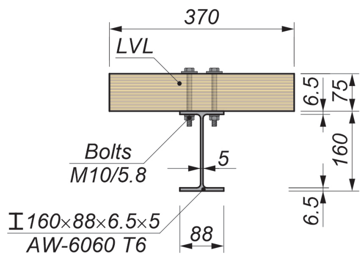
<table>
<tr><th>Test authors</th><th colspan="2">Cross-section</th></tr>
<tr><td rowspan="5">Saleh and Jasim [80–82]</td><td colspan="2">
</td></tr>
<tr><td>Girder</td><td>Height = 100 mm, aluminium alloy ($f_{0.2}$ = 191.84 MPa, f_u = 236.32 MPa)</td></tr>
<tr><td>Slab</td><td>Thickness = 18 mm, plywood slab (f_c = 18.03 MPa – parallel to face grain, f_c = 13.69 MPa – perpendicular to face grain)</td></tr>
<tr><td>Connectors</td><td>Self-drilling and self-tapping screws, and epoxy adhesive layer</td></tr>
<tr><td>Number of beams</td><td>4 beams subjected to static loads and 4 beams subjected to impact loads</td></tr>
<tr><td rowspan="5">Saleh and Jasim [80–82]</td><td colspan="2">
</td></tr>
<tr><td>Girder</td><td>Height = 100 mm, aluminium alloy ($f_{0.2}$ = 191.84 MPa, f_u = 236.32 MPa)</td></tr>
<tr><td>Slab</td><td>Thickness = 37 mm, plywood slab, (f_c = 18.03 MPa – parallel to face grain, f_c = 13.69 MPa – perpendicular to face grain)</td></tr>
<tr><td>Connectors</td><td>Self-drilling and self-tapping screws, and epoxy adhesive layer</td></tr>
<tr><td>Number of beams</td><td>4 beams subjected to static loads and 2 beams subjected to impact loads</td></tr>
</table>

Table 5 [cont.]

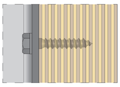
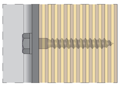
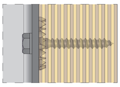
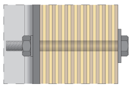
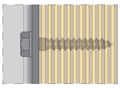
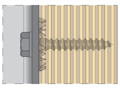
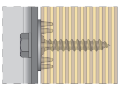
<table>
<tr><th>Test authors</th><th colspan="2">Cross-section</th></tr>
<tr><td rowspan="5">Chybiński and Polus [87]</td><td colspan="2">
</td></tr>
<tr><td>Girder</td><td>Height = 160 mm, AW-6060 T6 aluminium alloy
($f_{0.2}$ = 181.5 MPa, f_u = 209.8 MPa)</td></tr>
<tr><td>Slab</td><td>Thickness = 75 mm, LVL slab
($f_{c,0,k}$ = 40 MPa, $f_{t,0,k}$ = 36 MPa)</td></tr>
<tr><td>Connectors</td><td>Hexagon head wood screws (f_u = 598.9 MPa)</td></tr>
<tr><td>Number of beams</td><td>2</td></tr>
<tr><td rowspan="5">Chybiński and Polus [88]</td><td colspan="2">
</td></tr>
<tr><td>Girder</td><td>Height = 160 mm, AW-6060 T6 aluminium alloy
($f_{0.2}$ = 181.5 MPa, f_u = 209.8 MPa)</td></tr>
<tr><td>Slab</td><td>Thickness = 75 mm, LVL slab
($f_{c,0,\mathrm{mean}}$ = 53.8 MPa, $f_{t,0,\mathrm{mean}}$ = 41.9 MPa)</td></tr>
<tr><td>Connectors</td><td>M10 grade 5.8 bolts ($f_{0.2}$ = 419.5 MPa, f_u = 516.3 MPa)</td></tr>
<tr><td>Number of beams</td><td>3</td></tr>
</table>

The load-carrying capacity and the stiffness of the connections used in aluminium-timber composite beams were summarised in Table 6.

One can observe that the bolted connection had lower stiffness than the screwed connection due to the clearance between the bolt and the holes in the aluminium girder flange and the LVL slab. As demonstrated in Table 6, the load-carrying capacity and the stiffness of the connection increased with the increase of the screw diameter.

Last but not least, the use of toothed plate connectors as reinforcement in aluminium-timber screwed connections increased their load-carrying capacity. The aluminium-timber composite beams with screwed connections were almost fully composite beams because

Table 6. The load-carrying capacity and stiffness of the connections per one connector [87–89]

Connection	View	Load-carrying capacity [kN]	Slip modulus $k_{0.4}$ [kN/mm]	Slip modulus $k_{0.6}$ [kN/mm]
with 10 × 60 mm screw [87]		15.1	5.5	4.3
with 10 × 80 mm screw [89]		16.7	6.6	6.2
with 10 × 80 mm screw and a toothed-plate connector (type C2-50/M10G, Bulldog) [89]		21.5	6.4	5.9
with M10 grade 5.8 bolt (L = 115 mm) [88]		24.4	3.4	3.4
with 12 × 80 mm screw [89]		22.3	8.5	7.1
with 12 × 80 mm screw and toothed-plate connector (type C2-50/M12G, Bulldog) [89]		27.6	7.5	7.3
with 12 × 80 mm screw and toothed-plate connector (type C11-50/M12, Geka) [89]		30.1	6.7	7.0

the degree of the shear connection was equal to 0.97. The load-bearing capacity of the unrestrained aluminium girders increased 6.3 times after they had been joined with LVL slabs using screws (Table 4). The aluminium-timber composite beams with bolted connections were fully composite beams. The load-bearing capacity of the unrestrained aluminium girders increased 7.0 times after they had been joined with LVL slabs using bolts (Table 4). The rectangular stress block method was used to calculate the load-bearing capacity of the aluminium-timber composite beams. The experimentally determined load-bearing capacity of the aluminium-timber composite beam with bolted connections was 8.4% higher than the value obtained from the theoretical analyses (Table 4). The value of the load-bearing capacity of the aluminium-timber composite beam with screwed connections, obtained in the tests, was 7.5% higher than the value obtained from the theoretical analyses (Table 4). The rectangular stress block method works well for fully composite aluminium-timber beams.

The behaviour of aluminium-timber composite beams was also evaluated in numerical analyses. The finite element models of the aluminium-timber composite beam with screwed connections and the aluminium-timber composite beam with bolted connections were developed and verified against the experimental results. In both models, the shear connections were modelled using zero-length springs, the load-slip behaviour of which had been previously obtained in the laboratory push-out tests [87, 88].

Recently, the withdrawal strength of screws used for joining aluminium beams and timber slabs has been investigated [90]. The withdrawal load–displacement model of screws may be used to model the behaviour of zero-length springs in the vertical direction (the longitudinal screw axis) to refine the numerical model of the aluminium-timber composite beam with screwed connections.

4. Conclusions

New solutions and applications of aluminium members are still the object of research. Recently, composite structures with aluminium members have been investigated.

The main outcomes drawn from this review paper have been divided in three parts corresponding to three areas: aluminium-concrete composite beams, concrete-filled aluminium tube columns and aluminium-timber composite beams.

In the case of aluminium-concrete composite beams:

- The load-bearing capacity and the stiffness of aluminium girders increased after they had been joined with concrete slabs, e.g., the load-bearing capacity of the unrestrained aluminium girders increased 5.2 times after they had been connected with the concrete slabs using the demountable dowel-bolt shear connectors.
- The cooperation of concrete slabs and aluminium girders eliminates the problem of local buckling in girder flanges and lateral-torsional buckling in girders in simply supported composite beams. The modulus of elasticity of aluminium is only about 2 times higher than the Young's modulus of concrete. Due to this fact, the transformed slab area for a composite beam with an aluminium girder is larger than the transformed slab area for a steel-concrete composite beam.
- Aluminium-concrete composite beams can be joined using demountable shear connectors, i.e., dowel-bolt shear connectors.
- The rectangular stress block method worked well in the analysed aluminium-concrete composite beams.
- In the numerical models of aluminium-concrete composite beams with partial shear interaction and flexible or rigid shear connections as well as in the numerical models of fully composite beams with flexible shear connections, the shear connections can be modelled using zero-length springs the load-slip behaviour of which had been previously obtained in laboratory push-out tests or from theoretical analyses.
- In the numerical models of fully aluminium-concrete composite beams with rigid connections, shear connectors may be modelled as beams fixed to the aluminium girder flange and embedded in the concrete slab. The second option is to use the tie function to model the connection between the concrete slabs and the aluminium girders.

– The stiffness of the analysed connections with dowel-bolt shear connectors was relatively low because of the clearance between the connector and the hole in the aluminium girder flange. What is more, the connectors were non-preloaded. The tested connections were brittle and they showed signs of rib-shearing failure because relatively narrow ribs (44 mm) were used.
– The analysed composite beams with dowel-bolt shear connectors showed signs of rib-shearing failure. The ductility and the stiffness of their connections should be increased in future research. To increase the stiffness and the ductility of the connections in aluminium-concrete composite beams, the solutions demonstrated to be effective for steel-concrete composite beams and listed below may be applied and tested. For example, the use of waveform reinforcement may prevent rib-shearing failure [66]. Furthermore, waveform reinforcement used together with steel wire spiralled around shear connectors could reduce the effects of the concrete-related failure modes of shear connections and increase their ductility [67]. Moreover, the pre-tensioning of demountable shear connectors may increase the initial stiffness of connections [68]. Last but not least, the reduction of connector-to-hole clearances could increase the stiffness of shear connections [69].

In the case of concrete-filled aluminium tube columns:

– Aluminium tubes may be filled with concrete to create aluminium-concrete composite columns. The use of concrete inside aluminium tubes improves the capacity and the fire resistance of columns. Aluminium tubes act as stay-in-place formwork and they promote the confinement effect.
– Aluminium-concrete composite columns have higher ductility than their aluminium counterparts, because they contain a greater amount of material and because of the confinement effect.
– Comparing the intensity of the confinement effect in steel-concrete and aluminium-concrete columns, it is slightly lower in aluminium-concrete composite columns than in steel-concrete composite columns.

In the case of aluminium-timber composite beams:

– The load-bearing capacity and the stiffness of aluminium beams increased after they had been joined with timber slabs, e.g., the load-bearing capacity of the unrestrained aluminium beams increased 7.0 times after they had been joined with LVL slabs using bolts. The cooperation of timber slabs and aluminium beams eliminates the problem of local buckling in beam flanges and lateral-torsional buckling in simply supported beams. The modulus of elasticity of aluminium is only about 5 times higher than the Young's modulus of LVL. Due to this fact, the transformed slab area for a composite beam with an aluminium beam is larger than the transformed slab area for a steel-concrete composite beam.
– Aluminium-timber composite beams can be connected using demountable shear connectors, i.e., screws and bolts.
– To increase the load carrying capacity of screwed and bolted connections in aluminium-timber composite beams, toothed-plate connectors may be used as reinforcement. However, the strengthening with toothed-plate connectors is ineffective in improving connection stiffness.

– The rectangular stress block method worked well in the analysed aluminium-timber composite beams.
– In the numerical models of aluminium-timber composite beams with partial shear interaction and flexible or rigid shear connections as well as in the numerical models of fully composite beams with flexible shear connections, the shear connections can be modelled using zero-length springs the load-slip behaviour of which had been previously obtained in laboratory push-out tests or from theoretical analyses.
– In the numerical models of fully composite aluminium-timber beams with rigid connections, the tie function may be used to model the connection between the timber slabs and the aluminium beams.

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Elementy ze stopu aluminium w konstrukcjach zespolonych – przegląd

Słowa kluczowe: stopy aluminium, belki zespolone aluminiowo-betonowe, belki zespolone aluminiowo-drewniane, rury ze stopu aluminium wypełnione betonem, wyroby drewniane

Streszczenie:

W pracy przedstawiono przegląd zespolonych konstrukcji, w których zastosowano stopy aluminium. Omówiono aktualne kierunki badań nad konstrukcjami zespolonymi z dźwigarami ze stopu aluminium oraz możliwe ich zastosowania w budownictwie. W prezentowanych rozwiązaniach wykorzystano zalety stopów aluminium m.in. korzystny stosunek wytrzymałości do ciężaru, odporność na korozję oraz przydatność do recyklingu. Autorzy opisali zachowanie belek zespolonych

aluminiowo-betonowych oraz drewniano-betonowych, biorąc pod uwagę własne badania, jak i te znane z literatury. Dodatkowo, scharakteryzowano słupy zespolone aluminiowo-betonowe, słupek zespolony aluminiowo-drewniany zastosowany w konstrukcji fasadowej oraz wojskowy most składający się z kratownicy ze stopu aluminium, szalunku traconego, zbrojenia oraz betonu. Oprócz opisu elementów konstrukcyjnych, przedstawiono główne wnioski z ich analizy eksperymentalnej, teoretycznej oraz numerycznej. Połączenie dźwigarów ze stopu aluminium z płytami wykonanymi z betonu lub drewna zapewniło wzrost nośności oraz sztywności dźwigarów oraz wyeliminowano problem lokalnego wyboczenia pasa dźwigara oraz jego zwichrzenia.

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