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A research review on aluminium beam-to-column joints

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Abstract

With the upcoming release of the second generation of European standards for the design of aluminium structures (Eurocode 9), significant changes in design guidelines are on horizon. The design of aluminium joints is a major component of the improvements and novelties that will be presented in the new generation of this standard. Therefore, this paper provides an up-to-date research overview on aluminium structural joints focusing on beam-to-column joints as well as identifying knowledge gaps and opportunities in this research field.

Key words: aluminium, beam-to-column joint, HAZ, welding, mechanical joining, component method, adhesives

Pregled istraživanja aluminijskih priključaka nosač-stup

Sažetak

S nadolazećim izdanjem druge generacije europskih normi za projektiranje aluminijskih konstrukcija (Eurocode 9), na pomolu su značajne promjene u smjernicama za projektiranje. Projektiranje aluminijskih priključaka ključna je komponenta poboljšanja i noviteta koji će biti predstavljeni u novoj generaciji ove norme. Stoga ovaj rad donosi najnoviji pregled istraživanja aluminijskih konstrukcijskih priključaka s fokusom na priključke nosač-stup, kao i utvrđivanje nedostataka u znanju i prilika u ovom području istraživanja.

Ključne riječi: aluminij, priključak nosač-stup, ZUT, zavarivanje, mehaničko spajanje, metoda komponenata, ljepila

1 Introduction

Aluminium in its pure form is a low strength metal and as such is not suitable for the requirements of the modern construction industry. However, in combination with alloying elements such as manganese, magnesium, silicon, etc., aluminium is successfully used in the form of alloys. With their main favourable properties, high strength-to-weight ratio and pronounced corrosion resistance, aluminium alloys have great potential for use in primary load-bearing structures, especially in marine environments [1, 2]. Another factor in favour of aluminium alloys is the manufacturing process and recycling ability. Namely, the extrusion process allows the production of profiles from a variety of cross-sectional shapes [3] which cannot be produced from steel, concrete, timber, or plastic. Moreover, the possibilities of recycling aluminium are endless. Secondary production of aluminium (recycled aluminium) consumes much less energy (up to 20 times) [2] than primary production of aluminium, which is a big step towards carbon neutrality by 2050 [4] from a sustainability point of view. Considering these properties, aluminium alloys can certainly be considered as one of the key engineering materials today [5].

Among other design rules, the standard for the design of aluminium structures, EN 1999-1-1 [6], contains rules for the design of aluminium connections/joints. In the design of welded structural members and joints using hardened or artificially aged alloys, due consideration must be given to the reduction of mechanical properties that occurs in the vicinity of the welds, i.e., in the heat-affected zone (HAZ) [7]. According to EN 1999-1-1 [6] and [8], the local reduction of the mechanical properties of the base material due to welding can be up to 50% for 6xxx series aluminium alloys, whose mechanical properties are most suitable for use in structural engineering. On the contrary, several recent studies [9, 10] have shown that these reductions can be decreased by applying advanced welding techniques from the field of mechanical engineering in combination with insight into the actual stress distribution after welding. Such novel welding techniques open a space for the development of reliable, as well as economically and environmentally viable welded aluminium structures and joints.

In the current European standard for the design of aluminium structures EN 1999-1-1 [6], the design of aluminium beam-to-column joints is based on the component method. However, the component method, which is widely known and used for the design of steel joints, is not fully applicable to aluminium structures [11, 12]. There are several reasons for this, the most notable of which are: the influence of welding, which has not yet been adequately researched; the lack of research into the stiffness of the individual components of the joint, which can contribute to the overall stiffness of the joint; and, no less importantly, the justification for using typical extruded I-sections in the frame systems. The latter reason arises from the fact that the serviceability limit state criterion is very often relevant for the design of aluminium structures. Therefore, the logical choice, especially for the beam segment, is the use of lattice girders or special welded I-sections.

Nowadays, the use of adhesive bonded joints has been growing rapidly in various industries due to numerous advantages over traditional joining techniques (more uniform stress distribution, ease of production, the possibility of joining different materials, stability of the mechanical properties of the base material) [13, 14]. Consequently, adhesives hold higher potential for application in structural joints, especially in beam-to-column joints, but also open a whole range of unknowns - from the design their self to their durability.

However, for the mentioned innovative welded and bonded aluminium joints there are no normative design rules and thus it is not possible to assess their reliability. The second generation of the European standard for the design of aluminium structures prEN 1999-1-1:2021 [15] brings improved analytical expressions for bolted and riveted connections. It also brings changes related to the T-stub and the effective lengths of the column flange in bending. Other new features attracting attention include the introduction of a new type of connection - the bolt-channel joint, and the design of friction stir welds. In addition to the T-stub, two new components for the design of beam-to-column joints are included (column web in transverse tension and column web in transverse compression). Nonetheless, the introduced improvements are not yet sufficient for the component method to be reliably used for aluminium beam-to-column joints. For adhesive bonded joints reference is made to the manufacturer's specifications or the informative Annex P [15], where the connection must be designed in a way that only shear forces need to be transmitted and appropriate adhesives applied.

Since the standardized methods for the design of aluminium joints are not evaluated probabilistically, the question of the actual reliability level of such designed aluminium structures remains open. Therefore, the purpose of this paper is to provide an overall review of previous research on the behaviour of aluminium structural joints and their components, with a focus on beam-to-column joints.

2 Component method for aluminium beam-to-column joints

In everyday design practice, it is common to consider the joints between structural members as either fully rigid or pinned. Such an approach usually leads to inefficient structures [16]. Pinned joints, Figure 1.a, have no rotational stiffness, so they cannot transmit bending moment, although they do transmit axial and shear force.

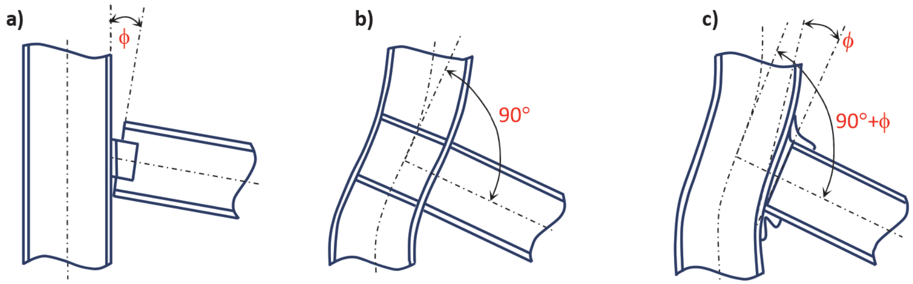
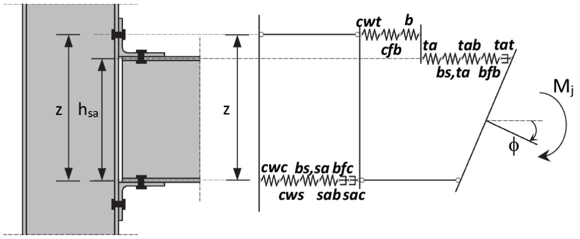


Figure 1. Joint types according to their behaviour: a) pinned, b) rigid, c) semi-rigid

Rigid joints, on the other hand, have rotational stiffness, and therefore can, transmit all types of loads, Figure 1.b. In reality, joints have a finite degree of rotational stiffness resulting from the deformability of all components from which the joints are composed, Figure 1.c. These types of joints are referred to as semi-rigid. Experimental research and the development of numerical methods have spurred the expansion of ideas for a more realistic classification of joints for everyday engineering practice. Hence, the complex behaviour of metal joints is effectively characterised by the component method, which is extensively investigated for steel joints [17]. The component method and the mechanical models describing each type of joint defines the basic characteristics of the joints. These characteristics are stiffness, bending resistance and rotation capacity. This method fits very well with the simplified mechanical model consisting of springs and rigid links, Figure 2. The essence of the component method refers to the characterisation of the load-displacement (F-Δ) curve for each spring. For the evaluation of the initial stiffness of the joint, only the linear stiffness of each component is required. However, for the assessment of the component's ductility, the knowledge of the nonlinear F-Δ response is necessary.



cws – column web in shear
cwc – column web in transverse compression
cwt – column web in transverse tension
cfb – column flange in bending
b – bolts in tension
ta – top angle in bending
bs,sa; bt,sa – bolts in shear
sab; tab; bfb – bearing resistance
bfc – beam flange and web in compression
sac – seat angle in compression
tat – top angle in tension

Figure 2. Schematization of the component method for beam-to-column joint with flange cleats [18]

A very few research is conducted regarding the components of which the most basic types of aluminium beam-to-column joints are constituted, not to mention that they are not probabilistically evaluated. It is also worth noting that there have been no experimental studies on the behaviour of welded beam-to-column joints in full-scale so far. All relevant studies are based on specific components of welded and bolted joints, mostly on a T-stubs [19-23]. Some recommendations for future research regarding the component method and aluminium joints are proposed by De Matteis et al. in [12].

For recalibration of the component method from steel to aluminium joints, the basic components of the aluminium joints need to be further investigated, as most of their design rules have been taken from EC3 [17] without detailed laboratory tests or numerical simulations. In general, experimental studies on full-scale welded and bolted beam-to-column joints must be conducted to obtain real M-ϕ curves and to recalibrate component method from steel to aluminium structural joints. Moreover, further studies are required to consider that, unlike steel, aluminium alloys exhibit nonlinear behaviour even at low deformations and have limited ductility, which affects the fracture strength of the joint [24].

3 Basic components of beam-to-column joints

3.1 General

In aluminium alloys, thermal expansion is twice as high as in steel, and the drop in the mechanical properties of the material at elevated temperatures is much faster and higher. Therefore, during welding, a deterioration in mechanical properties occur in the heat-affected zone – the area of base material that is not melted but has its microstructure properties altered. To understand the effects of welding on the heat-affected zone of aluminium alloys, different types of aluminium alloys and the potential for strength changes after welding need to be fully investigated. HAZ problems exist within welded and majority of bolted beam-to-column joints. If welded structural elements are used instead of extruded members, the effects of welding in such members should also be considered.

In recent decades, only a circumscribed amount of research has been done related to welded aluminium joints. One of the first attempts to seek a systematic and comprehensive understanding of the behaviour of welded connections was carried out by Soetens [25] and Matusiak [26]. Both of them analysed the heat affected zone (HAZ) and its impact on the behaviour and strength of welded connections. Moreover, Chan and Porter Goff [27] experimentally investigated the effects of a reduced strength zone on cruciform welded connections in terms of failure modes, ductility, and load-bearing capacity. The results of this study indicate, among other things, that weld defects can severely reduce the ultimate load bearing capacity of the mentioned connections. Another study on cruciform welded connections, as well as RHS welded T-joints was conducted by Zhang et al. [28]. The authors applied a new, holistic, modelling approach (thermal-mechanical analysis and mechanical analysis combined) to predict the fracture behaviour of aluminium welded joints. By using an interpolation function between two approaches, the HAZ dimensions of welded joints can be automatically determined from the weld microstructure data. Consequently, by implementing this approach in modern welding techniques (laser welding, friction-stir welding, etc.), fewer qualitative and quantitative reductions in HAZ can be achieved. Cheng et al. [10] have provided a comprehensive review of techniques that could improve the softening behaviour of aluminium joints. Several further studies regarding joint softening have been proposed in this paper as well.

Early attempts of numerical investigations on aluminium welded beam-to-column joints were made by Wang et al. [29], who reproduced the laboratory tests done by Matusiak [26]. Since the numerical results were found to be highly mesh dependent, reliable results were obtained by applying non-local plastic thinning to the welds and HAZ. This technique was recommended by the authors for modelling thin-walled aluminium structures with shell finite elements. In addition, numerical studies were carried out on the equivalent welded T-stub model, adopted in current version of EC9 [6], which reflects the behaviour of some elements of the joint in tension and compression. De Matteis et al. [11] in their research have proposed a numerical model with detailed characterization of HAZ that accurately reproduces the behaviour of the T-stub compared to the experimental results and the design method (‘’K-method’’) included in EC9 [6, 15]. More studies to evaluate the HAZ properties were carried out on aluminium T-section members with and without transverse welds as well as on stiffened aluminium panels [30, 31]. Both studies showed significant reduction on mechanical properties of the base material, although it was observed in [30] that it was highly influenced on weld location.

However, further studies on HAZ and welded joints need to be carried out so that characterisation of these components can be reliably and less conservatively used with the component method. In the continuation of this chapter, only the components of aluminium joints that have been subject of research so far will be presented.

3.2 Equivalent T-stub in tension

The most significant research related to bolted beam-to-column joints was conducted by De Matteis et al. [32] over two decades ago. This numerical study was based on aluminium T-stub joints where influence of behavioural parameters such as strain hardening effect, influence of HAZ and low ductility were analysed. Since this was the first extensive and comprehensive investigation of an aluminium T-stub component, the results of this numerical study were the basis for the evaluation of T-stub's resistance in the current EC9 standard [6]. It has been shown that the failure mechanisms of aluminium T-stubs differ from those made of steel, Figure 3(a). Furthermore, the aforementioned study proved that the equations used in EC3 [17] for steel T-stubs are quite accurate for aluminium T-stubs only when strain hardening is negligible. The assessment of the plastic resistance of the T-stub is based on the well-known principle of yield lines. Experimental and numerical studies on yield lines were carried out by Efthymiou [33]. For the type 1 mechanism, Figure 3.a, two basic yield lines were developed: at the flange-to-web junction and along the bolt axis, Figure 3.b. Other relevant numerical research on aluminium bolted T-stubs can be found in [34-37].

Recent experimental studies involved T-stub components connected by swage-locking pins under monotonic loading [38]. In this study, 30 specimens were tested which included failure modes, load-carrying, and deformation capacity as well as F-Δ response. Compared to the experimental results, the EC9 design rules for predicting the bolted T-stub's resistance were found to be conservative. The authors took their study a step further and suggested improvements using the Continuous Strength Method (CSM). The continuation of this experimental study was followed by extensive parametric numerical analysis [39]. The objective of this study was to validate the finite element (FE) model based on the experimental tests in [38] and provide a parametric study that included the preload effect in the swage-locking pins, the pin diameter, etc. Based on this study, a new method was proposed to predict the location and distance more accurately between the plastic hinges compared to the existing method in the EC9 standard for bolted T-stub.

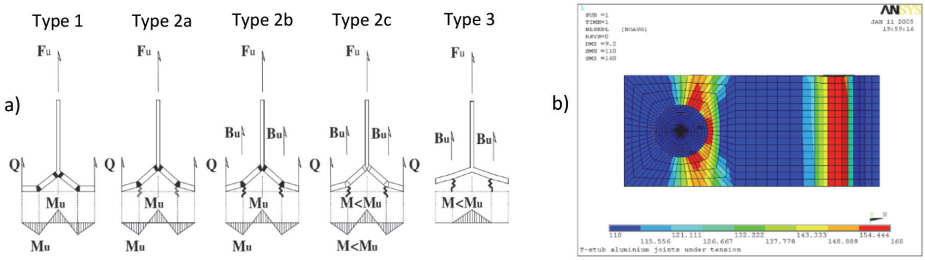


Figure 3. Aluminium bolted T-stub: a) Failure mechanisms [32], b) Typical yielding lines (zones) [33]

Wang et al. [40] investigated five full-scale aluminium top and seat angle cleats (TSAC) joints and three full-scale aluminium top, seat, and web angle cleats (TSWAC) joints connected by swage-locking pins, Figure 4. It should be noted that two different materials were used for the angle cleats: aluminium alloy AW 6061-T6 and stainless steel S304. The study found higher initial rotational stiffness and bending resistance when stainless steel cleats were used. In addition, the TSWAC joints proved to be more resilient than the TSAC joints. The authors pointed out that there were some unavoidable uncertainties since only one specimen of each configuration (8 configurations in total) was tested and no repeated tests were performed.

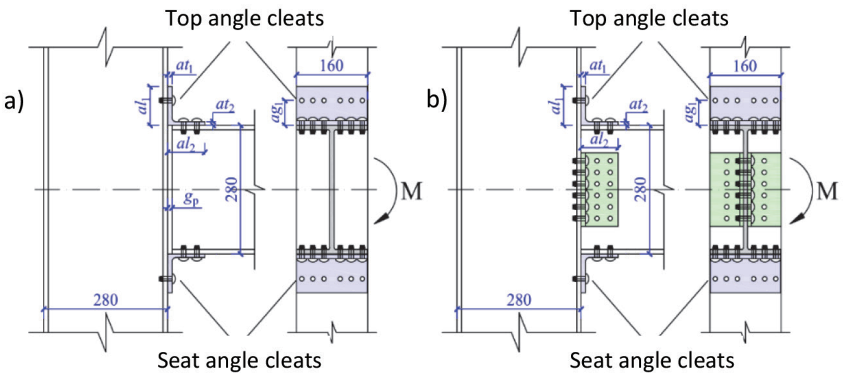


Figure 4. Test specimens of swage-locking pinned joints with angle cleats: a) TSAC joint, b) TSWAC joint [40]

3.3 Column web in transverse tension

The column web component subjected to transverse tension was part of the research work done by De Matteis and Brando [24, 41]. The authors investigated the influence of the HAZ and column axial load on the overall component behaviour by means of a parametric numerical analysis. It was concluded that column axial load reduces the component strength by 80% for column in compression and 20% for column in tension. The authors proposed a correction factor k_{cwt} to account these adverse effects. The results of these research works will be implemented in the second generation of EC9 [15].

4 Innovative beam-to-column aluminium joints

Nowadays, the use of innovative modular structures is on the rise and represents a key strategy to meet the requirements from a sustainability perspective. The targeted synergy of modular construction and versatile material such as aluminium, has the potential to improve productivity, efficiency, and quality of construction. Pi Home [42] is one of the great examples of aluminium innovative modular structures, Figure 5.a. Special attention is paid to the joints in such structures. Figure 5.b shows the detail of the innovative beam-to-column joint with specially extruded aluminium profiles using screw grooves. Macillo et al. [43] investigated experimentally and numerically the pull-out behaviour of similar screw groove connections. A total of 45 laboratory tests were carried out with three different screw slot configurations. The numerical model developed in this study was the basis for the extensive parametric analysis that led to the analytical expressions soon to be published in second generation of EC9 [15] for these types of joints.

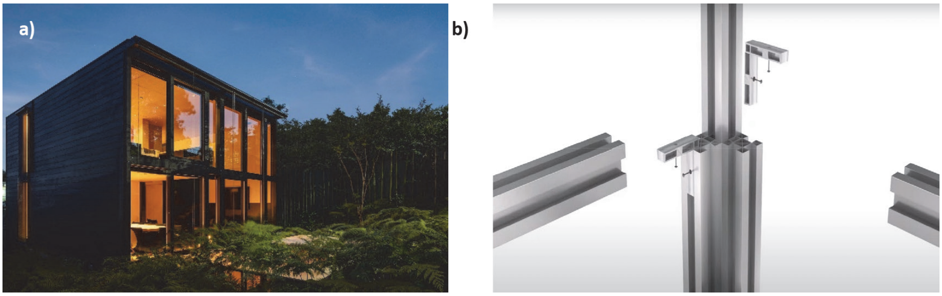


Figure 5. Pi Home: a) Modular aluminium structure, b) Innovative beam-to-column joint with screw grooves [42]

In the field of adhesive bonded joints, one of the industrially used joint types is the T-joint. Such joints are often found in the marine and aerospace industries [44]. However, most of the research relates to adhesive joint configurations like single-lap joints (SLJ) and double-lap joints (DLJ). The aluminium adhesively bonded T-joints, which are the subject of research in [14, 44, 45], indicate high ductility and resistance of such joints. Figure 6 therefore shows possible further research on the application of adhesives in aluminium beam-to-column joints proposed by the authors of this manuscript. Based on their preliminary numerical analyses, adhesives have potential to be used either in the form of strengthening the joints, Figure 6.a, or as a load-bearing component, Figure 6.b.

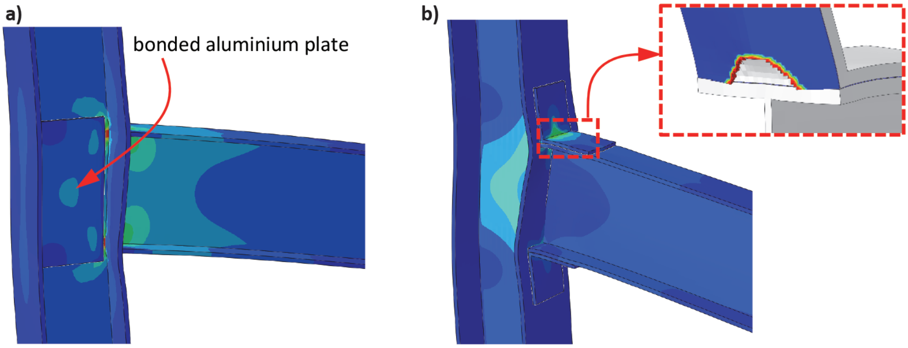


Figure 6. Aluminium beam-to-column joint: a) with bonded aluminium plate for strengthening column web, b) with bonded flange cleats

5 Conclusion

The design methods for characterisation of aluminium beam-to-column joint behaviour given in the current Eurocode 9 are slightly modified from Eurocode 3. The second generation of Eurocode 9 brings new analytical expressions for innovative connections and improvements related to the design of aluminium beam-to-column joints. Given insight into the research on aluminium connections/joints revealed a very small number of performed laboratory tests in general. Most research on welded joints are based on numerical simulations calibrated on laboratory tests conducted more than two decades ago. The problem of aluminium welding in terms of reduction in mechanical properties has not yet been sufficiently researched. However, the results of several recent studies on novel welding techniques are promising in terms of lower reductions of mechanical properties in the HAZ. Within this paper, the research on basic components of beam-to-column joints and current possibility of applying the component method to aluminium beam-to-column joints is briefly presented and discussed as well. Overall, laboratory tests and probabilistic evaluation of both welded and bolted beam-to-column joints in full-scale are essential for reliable recalibration of the component method from steel to aluminium joints. Nevertheless, there is an opportunity to develop innovative joining techniques (modern welding techniques, adhesive bonding, etc.) and to design reliable, economically, and environmentally viable structural aluminium joints and welded aluminium structures in general.

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