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The Development of Arc Stud Welding

Abstract: The article analyses the origins and initial stages of the development of the drawn arc welding of steel studs. The analysis is focused on the evolution of welding-related professional terminology in various languages. The article presents the properties and areas of application of shear connectors – some of the most popular connectors, used particularly often in civil engineering investments.

Keywords: arc stud welding; shear connectors; ceramic ferrule; drawn arc; Nelson; steel girders; composite structures

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The origins

The history, and particularly the origins, of the industrial implementation of arc stud welding have not been discussed in detail yet. Few publications state that the first successful tests of manual arc stud welding were performed as early as in 1915 [1÷3] by a British engineer Harold Martin [2÷4]. It is also possible to come across information, according to which the arc stud welding technology originated in industrial implementations of 1930, performed by workers of the US Naval Shipyard in New York [5]. Sporadically, it is believed that the inventor of the arc stud welding method was Andrew Foott-Stephens [6], who carried out his tests in the USA in 1940. However, it was Ted Nelson that went down in history as the pioneer of automated arc stud welding.

American legend

The year 1939 [7÷10] or (1940 [11]) is commonly regarded as the date of the first successful application of mechanised arc stud welding in production conditions. At that time, at the US Mare Island Naval Shipyard (Vallejo, California), one of the workers dealing with the fixing of steel threaded studs made an attempt at improving the procedure [11]. According to related sources, studs were used to join related deck layers [2, 3, 5, 8, 12]. Regrettably, there are no precise reference publications as regards shipyard products made using the above-named technique. An exception is a single mention attributing the role of the arc welding pioneer to Nelson. The mention also suggests that the origins of automated arc welding date back to 1934, the time of the construction of one of the aircraft carriers [12]. Information concerning the first application of the above-named joining technology in the building of aircraft carriers is repeated in several other sources, yet none of them is detailed [2, 13].
Taking into account the censorship of 1939/1940, the above-presented version of events seems questionable, as in the 1930s, the Pacific shipyard in Vallejo, where the American inventor allegedly worked, dealt with the construction

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and repairs of submarines and submarine tenders (i.e. auxiliary ships intended for the servicing, maintaining and supplying other ships). The last ship made in the docks of Mare Island before the outbreak of WW2 was the USS Henley (DD-391) destroyer, built from the autumn of 1935 and put into service in 1937. In turn, the last ship modernised in the shipyard before the commencement of military activities was the USS Langley (AV-3), which arrived at the shipyard in the autumn of 1936, being then an obsolete aircraft carrier and left the shipyard in 1937 as a seaplane tender [14÷15]. It cannot be excluded that Nelson performed the first tests of the arc welding of threaded studs as early as in the first half of the 1930s, i.e. during the conversion of the then obsolete USS Langley and that the development of the ultimately reliable welding technology took place several years after that. It is equally possible that Nelson never performed his works on any aircraft but on board another ship, not necessarily prepared for servicing seaplanes (e.g. the USS Fulton submarine tender, launched in December 1940) or on board of one of regularly launched and/or revamped ships in the shipyard of Vallejo (e.g. the USS Pompano, launched in March 1937, the USS Sturgeon finished in March 1938 or the USS Swordfish commissioned in April 1938) [14÷15].

The above doubts could not be dispelled even by representatives of the American corporation of Nelson Fastener Systems Company (recently incorporated into Stanley Engineered Fastening), i.e. a direct inheritor of the technical tradition and the capital of the company established by Ted Nelson. At the same time, the aforementioned representatives seem to suggest that the experiments with the new joining method were truly inspired by a sincere wish to help the heavy industry facing the oncoming World War 2. At the end of the day, Nelson received a prestigious award (class E [14]; in the category of work efficiency) granted by the US Navy for an invention which helped save as many as 10 million man-hours. However, the reliability of this patriotic message seems doubtful in view of the fact that the USA declared war on Axis powers only in December 1941 and that a federal act on providing Allied forces with military equipment (the so-called Lend-Lease Act) was adopted just six months before that.

It is relatively easy to question inventor's solely noble reasons for his declared will to serve the nation with more efficient work as in 1938 Edward F. Nelson (which was his name at the time) decided to file his ideas with the US Patent Office. In his first application, dated 5 July 1938 and approved on 27 February 1940, the author submitted eleven copyright claims concerned with the design of a so-called "welding apparatus". According to the creator, the aforesaid machine was to enable the arc butt welding of steel studs with large metallic areas. The author declared that the quality of joints offered by the solution would be higher than that obtained using the manual welding technique. In the above-named document, the designer of the prototype welding gun stated that his invention would greatly contribute to a significant decrease in the number of defective welds, eliminate the necessity of straightening bent studs and that the welding rate would not be lower than that obtained until then [16].

The inventor was significantly motivated by potential profits from the industrial application of his patents, which was confirmed by the fact that after only three months, E. Nelson submitted an application concerning improvements in the previous design of welding gun mechanisms [17] and another application (filed on 1 April 1940) [18] connected with the feeding of flux (improved arc ignition and spatter reduction). An impressive number of patent applications submitted by Nelson in the years to come, renewals of expired applications and starting own business enterprise demonstrated that the solutions offered by the inventor meet with favourable reception and, in subsequent years, enjoyed growing interest among representatives of industry.

European origins

It is worth to mention the achievements of the real pioneers of arc stud welding, who, regrettably have been forgotten by history. Within three years (1915-1918), the technology developed by H. Martin was implemented (as a result of his personal efforts) in the production processes applied in the Royal Navy Shipyard in Portsmouth (southern England) [1÷4]. In mid-1919, Harold Martin, Louis John Steele and Andrew Edward McCarthy started to seek the patent protection of their technical solutions in the United Kingdom [19]. However, initial successes did not translate into the popularisation of the joining method proposed by the inventors. One of the reasons that the inventors were forgotten could be the fact that the British Navy at the time of post-war decrease in demand for military equipment was not perceived as an attractive business partner, and yet was the first and only party potentially interested in the industrial application of this joining technology. However, the above-named technical solutions were not welcome by the shipbuilding industry of that time. The silence surrounding the achievements of the British inventors shows that their activities did not give rise to the popularisation of the projects in other sectors of the economy. Similar was the fate of an application for patent protection submitted to the Patent Office of the United States of America in June 1920 [20], petitions addressed to France's [21] and Denmark's [22] public administration bodies in July, applications made in Great Britain in January and November [23÷25] (concerning improvements in the previously proposed method) and the transfer of copyright in favour of London's Handstock Limited carried out before January 1922. In July 1920, before the submission of patent applications in Denmark and France, the three British business partners, acting on behalf the above-named company, reserved copyrights to their ideas in Germany. The aforesaid partners cited a priority right of one of them connected with a previous application made in 1919. However, sectors dealing with the production of aircraft parts, vehicle engine components or elements of electrical appliances, indicated by the partners as potential areas of arc stud welding applications, showed no interest in the invention. Chances of more extensive applications of the arc stud welding method decreased even further as a result of the economic downturn connected with the global financial crisis taking place at the turn of the 1920s and 1930s. It was only the policy of economic interventionism adopted in the early 1940s that changed the situation. Investments in the shipbuilding industry and the intensifications of armaments were responsible for "renaissance" of arc welding, underestimated for nearly two decades.

In the mid-1930s, the ideas of British shipbuilders and technological solutions of expired patens were addressed anew by the Nelson company, whose contribution to the development of the aforesaid joining technique established its position in the world of industry.

Terminology

Since the very beginning of the industrial application (1920s) of the arc butt welding of steel studs, the terminology concerning this joining technology was subjected to numerous modifications. Until the beginning of the 21st century, in official Polish technical documents related to several different methods of arc stud welding, only one term, i.e. "łukowe przypawanie elementów typu kołki z wykorzystaniem docisku" ("arc stud welding" in English; "Lichtbogen-Bolzenschweißen" in German) was used. In the PN-EN 24063:1993-09 standard (valid until 2002) [26], different variants of the process were assigned the same reference number, i.e. 781. The lack of appropriate differentiation in terminology concerning individual arc stud welding techniques became apparent as early as in 1978, when the International Organisation for Standardisation (ISO) issued (for the first time) the ISO 4063 standard, concerned with the terminology of welding methods and the numerical system of their identification [27]. It was only in another document (published at the beginning of the 21st century) concerned with the terminology of welding processes, i.e. PN-EN ISO 4063:2002-12 Spawanie i procesy pokrewne – Nazwy i numery procesów [28], being the translation of the English version of the EN ISO 4063:2000-02 standard Welding and allied processes – Nomenclature of processes and reference numbers, that the Polish standardisers decided to attribute separate numbers and unique names to individual arc stud welding methods (Table 1).

Table 1. List of references numbers and foreign terminology concerning individual process of arc butt welding of steel studs; authors' individual study based on publication [28].

Process/group reference number	Name in Polish	Name in English (BrE – British English; AmE – American English)	Name in German
7	Inne procesy spawalnicze	Other welding processes	Andere Schweißverfahren
78	Przypawanie kołków	Stud welding	Bolzenschweißen
783	Przypawanie łukiem ciągnionym kołków w osłonie łuku tuleją ceramiczną lub gazem osłonowym	BrE: Drawn arc stud welding with ceramic ferrule or shielding gas. AmE: Arc stud welding.	Hubzündungs-Bolzenschweißen mit Keramikring oder Schutzgas
784	Przypawanie krótkotrwałym łukiem ciągnionym kołków	BrE: Short-cycle drawn arc stud welding. AmE: Arc stud welding.	Kurzzeit-Bolzenschweißen mit Hubzündung
785	Zgrzewanie kondensatorowe łukiem ciągnionym kołków	BrE: Capacitor discharge drawn arc stud welding. AmE: Arc stud welding.	Kondensatorentladuns-Bolzenschweißen mit Hubzündung
786	Zgrzewanie kondensatorowe łukiem ciągnionym kołków z końcówką zapłonową	BrE: Capacitor discharge stud welding with tip ignition. AmE: Arc stud welding.	Kondensatorentladuns-Bolzenschweißen mit Spitzenzündung
787	Zgrzewanie kondensatorowe łukiem ciągnionym kołków z niskotopliwym pierścieniem	Drawn arc stud welding with fusible collar	Bolzenschweißen mit Ringzündung

Note: Process 781 according to PN-EN 24063:1993 was replaced with methods 783 ÷ 787.

Currently applied foreign terminology concerning discussed methods can be found in the latest standard by the International Organisation for Standardisation ISO 4063:2009-08+AC1:2010-03, adopted unamended by CEN as the EN ISO 4063:2010-12 standard. The above-named standard has been approved by the Polish Committee for Standardisation (Polish acronym - PKN) exclusively in its original wording, without translation [30].

Until today, the only attempt at the complex classification of the terminology of various welding processes (including arc stud welding) in the Polish language has been undertaken by research workers of Instytut Spawalnictwa in Gliwice (Table 2). Bearing in mind that the "lack of official translation of a given term in another language (...) often results in ambiguity and various interpretations of the text of a given standard" [29], the then Director of Instytut Spawalnictwa, J. Pilarczyk (Professor PhD (DSc) Habilitated Eng.), decided to establish a special working group. Supervised by B. Czwórnóg (PhD (DSc) Habilitated Eng.), in March 2012, the team published the results of their works in the form of guidelines W-12/IS-95. The above-named document, constituting the set of Polish terminology and corresponding terms on foreign languages, was based on regulations of the then valid PN-EN ISO 4063:2011-03 standard Welding and allied processes – Nomenclature of processes and reference numbers [30]. The terminology suggested in the standard seems to significantly more aptly, briefly and accessibly characterise the nature of individual arc stud welding processes than translated terms contained in the previous version of the related PN (Polish standard). At the same time, in the above-named guidelines, the authors abandoned the idea of introducing entirely new terms or expressions in favour of long-existing and well-established entries in the Polish technical terminology.

In spite of an attempt undertaken jointly by CEN and ISO to standardise terminology, since the very beginning the official terminology applied in the USA has been lacking the differentiation between individual arc stud welding methods, collectively referred to as "arc stud welding". The only exception is method 787, since the turn of the centuries having its unique name of "drawn arc stud welding with fusible collar". It is possible that, within the next few years, the above-presented situation will change along with the publication of another edition of the 4063 series standard (subject to periodic (five-year)) validation. Based on the positive (and, as of today, the only) assessment of the document, on 09 January 2015 the representatives of the International Organisation for Standardisation extended the validity of the latest edition of the standard. However, 27 November 2017 saw a decision on the renewal of the validation procedure [31], whereas 11 May 2018 was the date of the registration of a new project on Technical Committee/Sub-committee programme agenda TC44/SC7. According to information provided by the members of Working Group 2 (WG2), who, presided over by G. Krämer [32], are working on the concept of the subsequent, i.e. fifth version of the standard (not including the corrigendum of 2010), until today the undertaking has remained at its initial stage, where a newly created document continues to have status of AWI (Approved Work Item) [33].

Table 2. List of currently applied reference numbers and foreign terminology concerning individual process of arc butt welding of steel studs as well as Polish terms suggested by Instytut Spawalnictwa in Gliwice; authors' individual study based on publication [29] and [30].

Process/group reference number	Name in Polish	Name in English (BrE – British English; AmE – American English)	Name in German
7	Inne procesy spawalnicze	Other welding processes	Andere Schweißverfahren
78	Zgrzewanie łukowe kołków	Stud welding	Bolzenschweißen
783	Zgrzewanie łukowe kołków z poderwaniem i użyciem pierścienia ceramicznego lub gazu osłonowego	BrE: Drawn arc stud welding with ceramic ferrule or shielding gas. AmE: Arc stud welding.	Hubzündungs-Bolzenschweißen mit Keramikring oder Schutzgas
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786	Zgrzewanie kondensatorowe kołków z końcówką zapłonową	BrE: Capacitor discharge stud welding with tip ignition. AmE: Arc stud welding.	Kondensatorentladuns-Bolzenschweißen mit Spitzenzündung
787	Zgrzewanie łukowe kołków z użyciem pierścienia topliwego	Drawn arc stud welding with fusible collar	Bolzenschweißen mit Ringzündung

Selected industrial applications of steel studs

Presently, steel studs (also referred to as bolts or pins) used in arc welding techniques, are available in many variants. Within such a vast range of products, normalised in accordance with EN ISO 13918, an important position is occupied by cold-shaped shear connectors made of unalloyed steel, used in civil engineering since the 1960s (Fig. 1), where the aforesaid steel studs are particularly popular in bridge spans, multi-storeyed car parks, shopping malls (Fig. 2) and other large-area and multi-storeyed (e.g. residential or office) high-rise buildings.

In building structures, studs are used as connectors of the two primary (steel and concrete) component elements of subsequent floors of a building. The mechanical and permanent joint of steel girders and concrete slabs (placed/resting on the girders) makes it possible to include such composite elements in engineering calculations as single, inseparable and highly prefabricated structural elements, the use of which enables the significant reduction of assembly/fixing time at the construction site. No less important is the relatively low load-carrying capacity of joined products, enabling the reduction of their design height [34, 36, 37].

Fig. 1. Shear connectors with heads of various diameters and studs of various lengths along with ceramic ferrules (necessary for welding performed in accordance with EN ISO 4063: 783); the mat, black or dark grey colour of the connector surface results from the phosphatising of the connectors to increase their corrosion resistance; authors' own source by courtesy of BROSET Sp. z o.o.

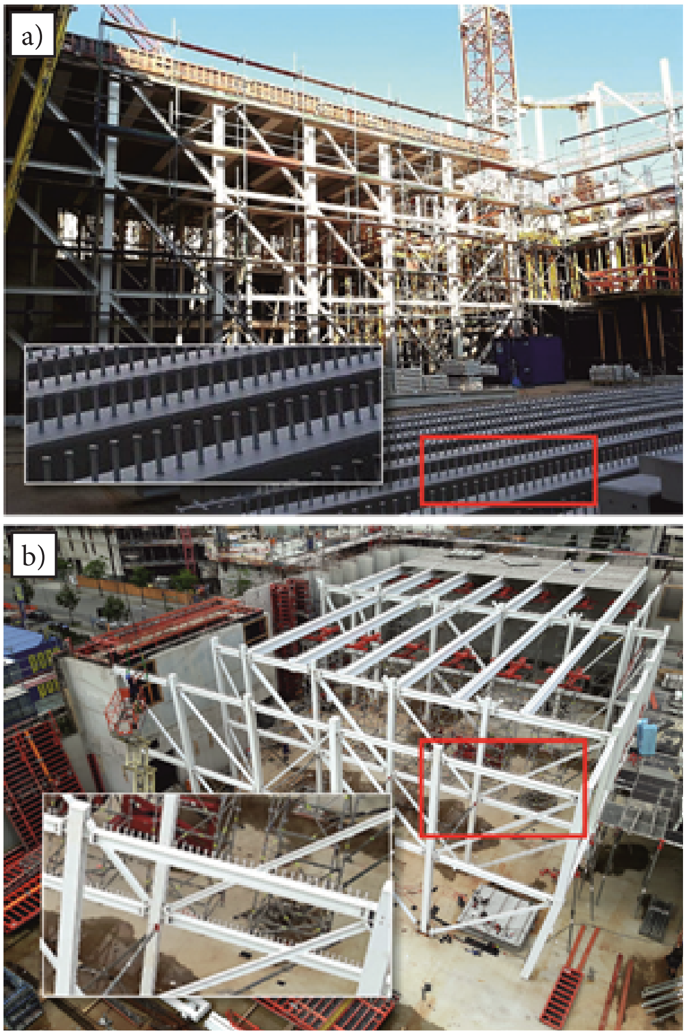

Fig 2. Steel load-bearing structure of a Mercedes dealer-service centre in Berlin during assembly works; visible numerous crossbars (Riegel in German) with studs welded to the internal surfaces of crossbar flanges, placed (afterwards) between supporting columns; authors' own source by courtesy of Spannverbund GmbH

The high strength of steel-concrete elements is the result of the simultaneous use of various properties of both composite components. The presence of studs welded to the surface of steel elements, responsible for the transfer of tensile stresses, increases the rigidity of the entire support structure of a building. At the same time, it is possible to provide the reliable joint of the framework with concrete slabs placed on successive floors of the building, aimed to counteract compressive forces (Fig. 3). The studs used in the above-presented manner transfer longitudinal shear forces acting between steel beams and concrete layers placed (resting) on them (Fig. 4) and protect the slabs against being torn off the girders. The resultant force of compressive stresses present in concrete mix affects the connector on the eccentric (a) located at a certain distance from the area of contact between joined elements. Its value corresponds to the value of delamination force (Ft) of a component part of such a composite product, acting in the contact area [36, 38].

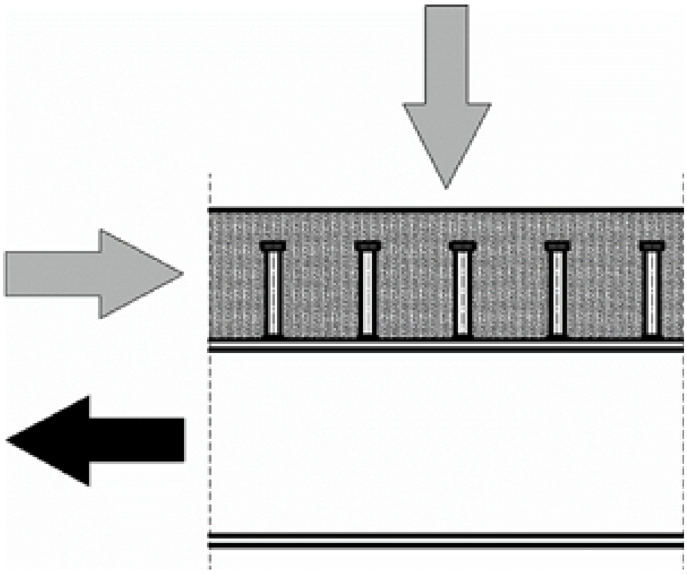

Fig. 3. Schematic diagram presenting forces affecting the steel structural girder with the studs and the layer of concrete mix, placed on the external surface of the upper shelf (upper flange); authors' individual study based on publication [34].

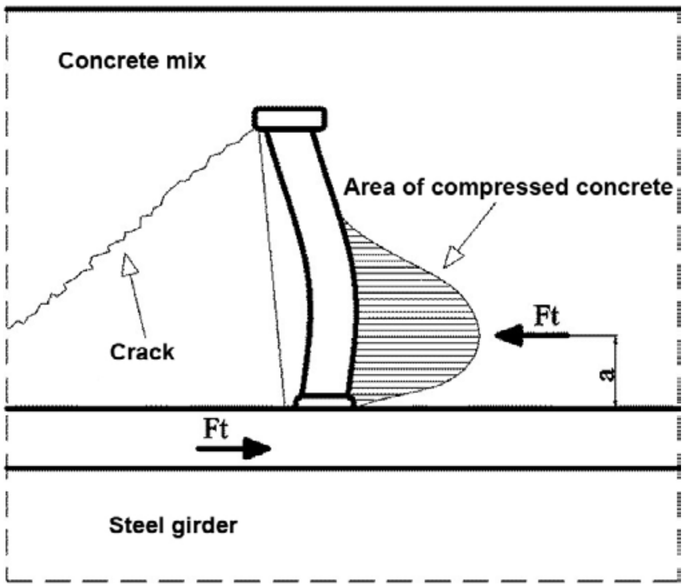

Fig. 4. Schematic diagram showing the operation of the shear connector – transfer of transverse load (shear force) in the joint of the steel girder with the concrete slab; authors' individual study based on publication [36]

The exact location of the resultant force is determined by dependences between the elasticity moduli of both building materials. Along with a decrease in concrete elasticity, the line of force action moves to the half of the stud height. The load-carrying capacity of such a joint is determined by the rigidity of concrete and that of steel. Because of the fact that the mechanism of the stud connector assumes the occurrence of the shear and bending of the study body, the design load-carrying capacity of the stud itself acquires particular significance. The above-named load-carrying capacity is determined on the basis of two correlations presented below, leading to the obtainment of a lower value [36, 39]:

$$P_{Rd} = 0.8 f_u \frac{\pi d^2}{4\gamma_V} \quad (1),$$

$$P_{Rd} = 0.29 \alpha d^2 \sqrt{f_{ck} E_{cm}} \frac{1}{\gamma_V} \quad (2),$$

where

f_u – tensile strength (R_m) of the steel, the stud is made of, MPa;

d – nominal external diameter of the stud, mm;

γv – partial safety factor, assumed as amounting to 1.25, [–];

E_{cm} – mean value of the secant elasticity modulus of concrete, GPa;

α – factor dependant on the geometry of the stud used, defined as:

$\alpha = 0.2(h_{sc}/d + 1)$ for $3 \le h_{sc}/d \le 4$,

$\alpha = 1$ for $h_{sc}/d \ge 4$,

h_{sc} – total height of the welded stud.

The ability of a joint to transfer loads can be expressed using the following dependence [36, 39]:

$$F_t \le n_f P_{Rd} \quad (3).$$

The above-presented dependence is regarded as sufficient if force (F_t) shearing such a joint has been determined in accordance with the guidelines of Eurocode 4, does not exceed the value of the product of the design load-carrying capacity of a single stud (P_{Rd}) and the number of such studs (n_f). Studs taken into consideration are those welded in the girder area, located between the support and the cross-section of the highest bending moment.

At the same time, the anchoring of stud connectors in concrete mix chambers increases the fire resistance of joined beams. In the case of a fire in the building, the effect of high temperature on the steel structure is reduced by concrete layers, effectively insulating the metal frameworks. The impeding of heat flow makes it possible to maintain the high load-carrying capacity of steel structures for an adequately long time, e.g. sufficient for the evacuation of the building. Usually, the distribution of temperature in the cross-sections of concrete-steel composite structures (obtained in simulations of fire thermal effects) indicates the presence of zones having a temperature of up to approximately 300 °C, stretching in the central parts of webs, constituting important load-carrying elements of the structure [34, 37].

Metallic joints of studs with supporting elements of steel structures, obtained across entire cross-sectional areas of studs, are usually made using the DASW technique (DASW - drawn arc stud welding), i.e. drawn arc stud welding with ceramic ferrule or shielding gas (EN ISO 4063: 783). An important structural detail of studs, enabling the use of the above-named method, is constituted by aluminium "ignition tips" located on the frontal surfaces of studs (Fig. 1). Dimensional series of types and requirements concerning the fabrication of such studs is specified in international technical standards, e.g. Eurocode 4 documents [35, 36]. The most common in civil engineering projects are shear connectors (SD type), i.e. smooth studs with a head (referred to as Kopfbolzen in German), having a diameter restricted within the range of 16 mm to 25 mm and a length restricted within the range of 50 mm to 250 mm (Fig. 5). The above-named shear connectors are characterised by relatively high plasticity and load-carrying capacity nearly identical in all directions (providing the easy redistribution of loads affecting the studs). The SD type studs, commonly used in ceilings containing monolithic and prefabricated boards successfully and simultaneously transmit shear, tensile and even delamination forces. The high ductility of the connectors translates into the high ability of joints in steel-concrete ceilings subjected to transverse stresses to deform in a plastic manner. The precondition of the aforesaid favourable phenomenon is the obtainment of the total length of the studs (measured after welding) amounting to at least a quadruple of a stud diameter [34, 36, 37].

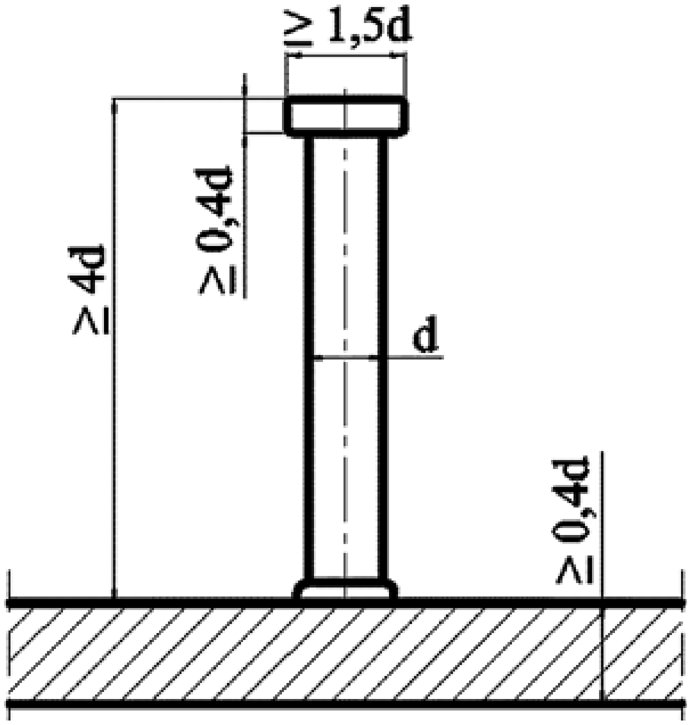

Fig. 5. Geometrical dependences of the SD type connector after arc welding; authors' individual study based on publication [36] and [40]

In cases of applications involving monolithic boards, the completion of the joining of the studs with the surfaces of steel beams and the fixing of such elements in appropriate areas of the structure is followed by the covering of girders (on the stud side) with layers of concrete mix. Properly designed and made elements of a building structure containing welded studs placed in concrete mix (e.g. anchors, Fig. 6) ensure the safe transfer of loads reaching even the ultimate tensile strength of unalloyed steel (Fig. 7). Procedures concerning the use of studs in projects implemented in the countries of the European Union are governed by regulations of the European Organisation for Technical Assessment (EOTA). For example, in the Federal

Republic of Germany such regulations are contained in ETA-03/0039 (concerning studs made of unalloyed steel and manufactured by Köster & Co.) and ETA-03/0040 (concerning elements made of stainless steel by Köster & Co.) [33].

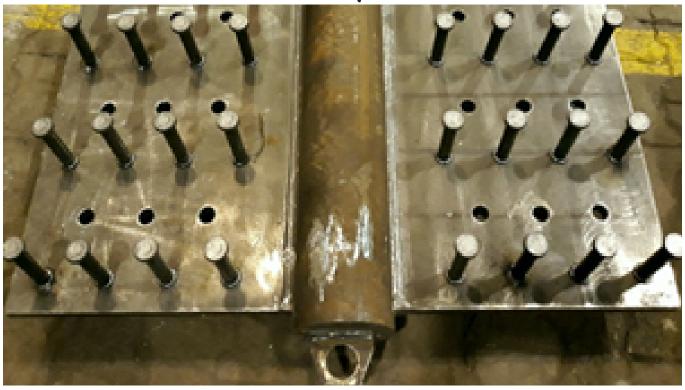

Fig. 6. Anchoring plates of the column head in a workshop directly after the process of stud welding; authors' own source by courtesy of BROSET Sp. z o.o.

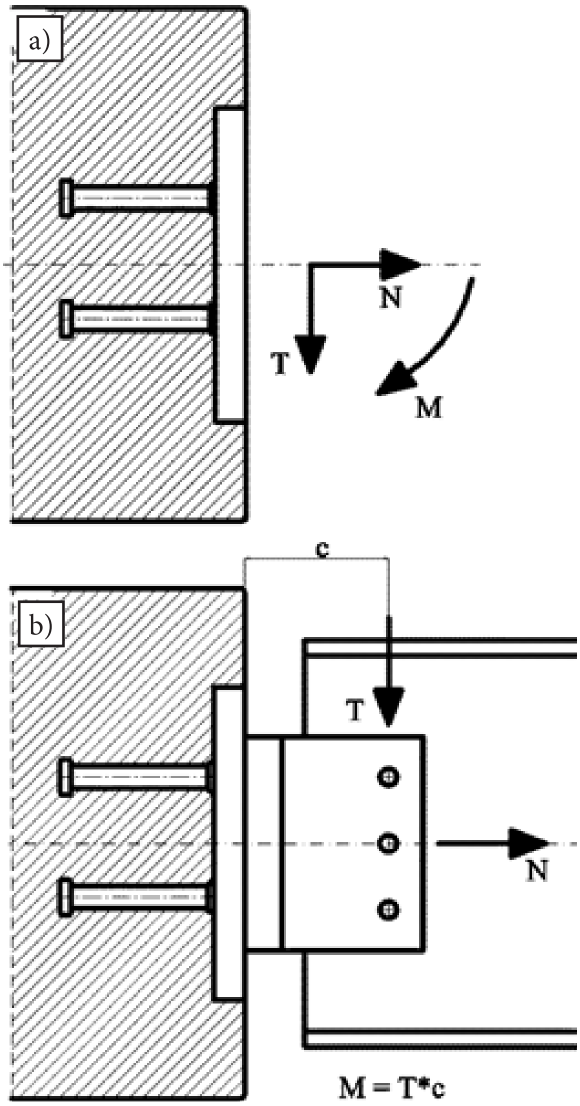

Fig. 7. Schematic diagram presenting directions of forces and moments present in: a) steel anchor with welded studs, placed in concrete mix; b) steel girder connected with the anchor with welded studs, placed in concrete mix; authors' individual study based on publication [33].

Equally often, steel studs are applied in the prefabrication of high composite columns used as structural elements of high-rise buildings. In addition to the placement of conventional rebars in parallel to the web and the application of a steel hollow section as the column shell, the use of the studs reinforces the joints of steel profiles constituting the core of the structure with concrete mix. Quite often it is possible to come across structural solutions of columns, where the role of the core is played by a stack of hot-rolled thick plates welded with one another. The studs are welded to the sheets and, afterwards, the whole is "girded" with a "basket" made of rebars, placed in the boarding and poured over with high strength concrete (because of the fact that such load-carrying columns are not provided with the external reinforcement shell – see Fig. 8) [33].

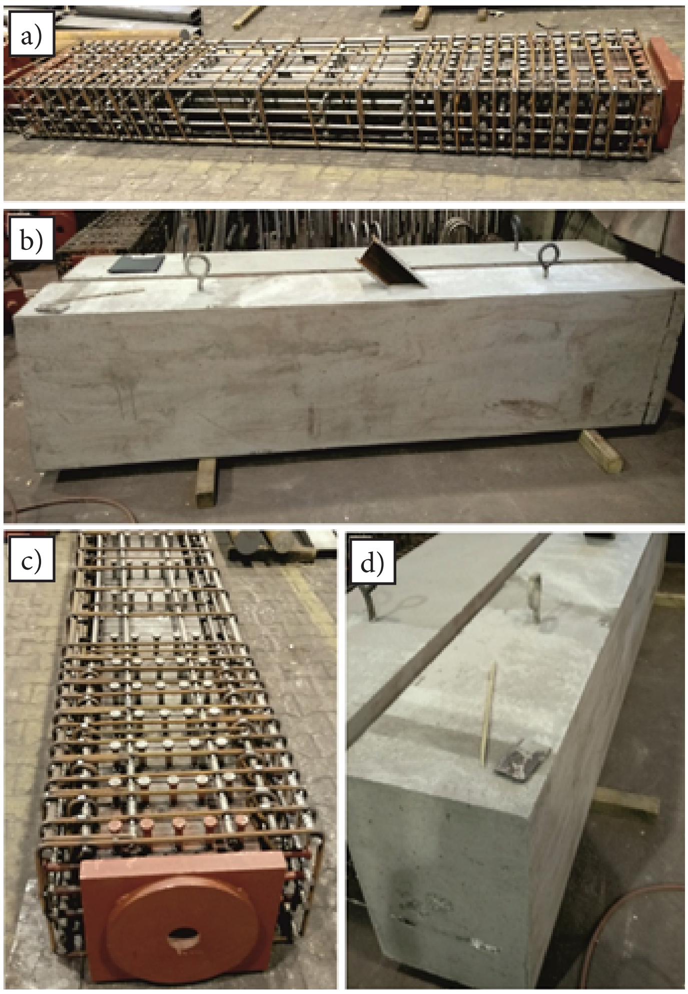

Fig. 8. Exemplary structures of load-carrying pillars made using stud connectors without the external shell: a) and c) before placing the concrete and b) and d) after placing the concrete; authors' own source by courtesy of BROSET Sp. z o.o.

Summary

Shear connectors owe their popularity in various civil engineering load-carrying systems to high mechanical strength and the plastic model of deformation providing the redistribution of stresses within a wide range as well as to their high rigidity and resistance to delamination forces. The privileged position of studs in industry is also connected with their simplicity and the fast and reliable joining of studs with metallic surfaces.

It should be noted that the above-presented popular technology, without which it is impossible to imagine the construction of long-span bridges or high-rise buildings, is one of the oldest and still used arc welding methods, the popularisation of which took many laborious years.

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