

Izabela TYLEK¹

SHAPING OF ARCHITECTURALLY EXPOSED STEEL STRUCTURES

Architecturally Exposed Structural Steel (AESS) is steel that must be designed to be structurally sufficient to support the primary needs of the structure and – at the same time – remains exposed to view, being a significant part of architectural language of the building [4, 6]. The quality requirements of AESS typically exceeds the requirements of Standard Structural Steel (SSS), what increases the time and costs of the design and execution of AESS. Currently used classification of AESS distinguishes 5 categories of execution quality. This categorization has a hierarchical structure, each higher category of structure execution contains all the properties of lower category. The basis of presented classification is the degree of human visual perception of the structure. It is mainly related to the distance of the potential observer from the structure, which allows in varying degrees to see the details of structure execution. Joints and connections are the main means of architectonic expression in architecturally exposed steel structures. The principles of joints and connections shaping in AESS are the same as for SSS but additionally some requirements to the expected aesthetic are formulated. This additional requirements cause that AESS can be significantly (even a few hundred percent) more expensive than SSS with exactly the same functionality and durability. However, PN-EN 1090-2 [7] gives no provisions about AESS executions, which may impede mutual understanding between architect, structural engineer, contractor and investor.

Keywords: exposition of steel structure, classification of AESS, higher quality requirements, higher costs of AESS

1. Introduction

Exposition of steel structure in architecture of public buildings is not a new trend. Many of the 19th century buildings – built during the initial stage of steel structures development – utilize architecturally exposed structural cast iron with ornate decoration that imitated carved stone elements (Fig. 1).

High costs of cast iron elements manufacturing, particularly in the case of their reshaping, caused that their degree of repetitiveness was very large, which limits the freedom of architectural forming of the building. Additional disadvantage

¹ Corresponding author: Izabela Tylek, Cracow University of Technology, ul. Warszawska 24, 31-155 Kraków, +48126282372, itylek@pk.edu.pl



Fig. 1. Interior of the Oxford University Museum of Natural History, built 1855-1860, Oxford, England (author of photography: nz_willowherb [10])

of cast iron – its low ductility – was the cause of a few spectacular failures of the 19th century bridges, e.g.: Dee Bridge (1847), the Tay Bridge (1879) and the Portland Road Bridge (1891). The second half of the 19th century brought the technology development, i.e. mass production of relatively cheap steel and rolling techniques of plates and profiles what increased application of steel structures in building industry. However, steel structures made of hot-rolled elements was considered to be visually heavy and aesthetically unattractive; additionally – riveted joints were very labour- and time-consuming. The above disadvantages combined with relatively fast degradation of steel element rigidity due to fire caused that for many decades steel frame structures of public buildings were hidden under the masonry or concrete cladding.

Initiated in late 1940s architectural style, later called Brutalism from the French word “brut” (“raw”), placed emphasis on the exposure of raw building materials and constructions producing expressive, minimalist forms. Built in the UK in 1954, Hunstanton Secondary Modern School in Norfolk became one of the flagship examples of this style, in which probably for the first time steel frame structure of public building was deliberately exhibited, revealing the architectural rhythm with repeated structural elements made of ordinary steel I-beams. Development of steel manufacturing and joining, which took place in the second half of the 20th century, made possible to design and execute large-area public buildings with large spans and large glazed area providing appropriate amount of natural light. Steel, because of its high strength to self-weight ratio, perfectly suited for this purpose, allowing shaping slender, visually

light structural elements with small cross section dimensions. Wide utilization of steel hollow sections and ties has become a characteristic feature of the developing from the 1970s architectural style known as high-tech architecture. Exposed structural elements are often shaped using the method called by T.M. Boake “a force-varied expression” [4]. It consists of intentional variation of cross-section dimensions of exposed steel elements, depending on the force sign and magnitude. In order to increase the architectural expression, many objects of this type have unnecessarily complex supporting system that can be replaced by simpler, but visually less impressive, one.

It should be noted that modern structural elements and their connections more often become the subject of architectural design. If the structural element performs also aesthetic function, it requires additional work effort of an architect, structural engineer, steel structure manufacturer, and erector. For this reason, architecturally exposed steel structures can even be several times more expensive than the standard steel structures.

2. Classification of architecturally exposed steel structures

Popularisation of architecturally exposed steel structures in combination with a variety of applied solutions and their high costs, caused the need to create a reference document, which would be a point of reference to facilitate the understanding between investors, architects, structural engineers and contractors. The first work which introduced currently used (Table 1) classification of architecturally exposed structural steel (AESS) was the study of the Rocky Mountain Steel Construction Association and the Structural Engineers Association of Colorado published in 2003 [2]. This proposal was introduced to Canadian standard [5] in 2009, American standard [1] and Australian/New Zealand standard [3] in 2016.

Classification presented in Table 1 distinguishes 5 categories of execution quality for architecturally exposed structural steel (AESS), denoted as AESS 1 ÷ AESS 4 and AESS C, which exceed quality requirements specified in execution standards for standard structural steel (SSS). This categorization has a hierarchical structure, each higher category of structure execution contains all the properties of lower category. The exception is AESS C category, which as defined, is intended for individual requirements that can be freely selected from the properties set provided in the classification or additionally specified by the architect. The basis of presented classification is the degree of human visual perception of the structure. It is mainly related to the distance of the potential observer from the structure, which allows in varying degrees to see the details of structure execution.

According to AESS category, quality requirements for the structure execution are defined. They may concern: quality of weld and element surface finishing, geometric tolerances or the type of joints used. The specific requirement, which may optionally be formulated for category AESS 2 or higher, is performance of mock-up, usually for joint or part of the structure. Mock-ups are

Table 1. Category array for specifying AESS based on [2]

Characteristics	AESS C	AESS 4	AESS 3	AESS 2	AESS 1	SSS
1.1 Surface preparation to SSPC-SP-6 [8]		•	•	•	•	
1.2 Sharp edges ground smooth		•	•	•	•	
1.3 Continuous weld appearance		•	•	•	•	
1.4 Standard structural bolts		•	•	•	•	
1.5 Weld spatters removed		•	•	•	•	
2.1 Visual samples		optional	optional	optional		
2.2 One-half standard fabrication tolerances		•	•	•		
2.3 Fabrication marks not apparent		•	•	•		
2.4 Welds uniform and smooth		•	•	•		
3.1 Mill marks removed		•	•			
3.2 Butt and plug welds ground smooth and filled		•	•			
3.3 HSS weld seam oriented for reduced visibility		•	•			
3.4 Cross sectional abutting surface aligned		•	•			
3.5 Joint gap tolerances minimized		•	•			
3.6 All welded connections		•	•			
4.1 HSS seam not apparent		•				
4.2 Welds contoured and blended		•				
4.3 Surfaces filled and sanded		•				
4.4 Weld show-through minimized		•				
C.1						
...						
Estimated cost premium [%]	20÷250	100÷250	60÷150	40÷100	20÷60	0

used to carry out the arrangements and getting multilateral acceptance of the visual aspects of structure final form. They may take the form of scaled or full-scale physical mock-ups or virtual rendered 3D images, which can be relatively easy created by using computer programs for steel structures 3D detailing, e.g. Tekla Structures, Bocad, Advance Steel, etc. The necessity of mock-up execution, particularly in the case of physical full-scale mock up, must be clearly indicated in the design documentation, because it requires additional costs and time which must be included in the schedule of construction works.

The AESS 1 category includes steel structures that, despite the fact that they are visible, are not architecturally dominant elements and their distance from the observer prevents seeing structural details such as welds quality or joint gap distances. They don't focus attention within observed space, usually have the same colour as the background and are often underexposed, remains in the shadow (see Fig. 2).



Fig. 2. Stand roof structure of Cardiff City Stadium, Cardiff, Wales (author of photography: Jon Candy [10])

The AESS 2 category includes structures that can be observed from a distance of not less than 6 m, but their shaping constitutes a significant part of the architectural composition of the building. These are often a visible, well lit part of the roof structure or high-level ceilings. Similarly as in AESS 1, distance between the observer and the structure does not allow for assessing the construction details quality (Fig. 3).



Fig. 3. Roof structure of Edmonton City Hall, Edmonton, Canada (author of photography: Mack Male [10])



Fig. 4. Concourse B of O'Hare International Airport, Chicago, USA (author of photography: joevare [10])

The AESS 3 category applies to structures that can be seen from a distance of less than 6 m and even touched by the public. This allows to see details and imperfections of elements surface finishing such as grind marks. Typical structures of this category structures include terminals, airports, shopping centres, etc. (Fig. 4).

The AESS 4 category is the highest category of steel structure execution quality, it includes highly exposed elements, dominating in the architectural composition of the building. In this type of structure, the architect's intention is to present the form of structural element as its unique visually exposed geometric property (Fig. 5). In this category, structures are often composed of custom elements, manufactured on investor's individual order, e.g.: connection parts made of cast steel, tapered hollow sections, etc. Welded joints with grinded weld face are often used. The element surfaces are also grinded and then surface defects are supplementing with special synthetic filler. This labour consuming surface treatment is required for structures covered with high gloss topcoats, which due to the high light reflection coefficient, greatly reveal all geometrical imperfections of the surface.



Fig. 5. Copernicus Airport Wrocław, Wrocław, Poland (author of photography: Paweł Żwirek)

Careful steel surface preparation in combination with other treatments, makes that structure is visually deprived of any characteristics allowing to identify the material of which it was made of. The examples of two contemporary structures executed as AESS 4 are shown in Fig. 6–8.



Fig. 6. Amazon Spheres – spherical conservatories serve as employee lounge and workspace located on the headquarters campus of Amazon company in Seattle, USA, completed in January 2018: steel structure under construction (author of photography: SounderBruce [9])



Fig. 7. Amazon Spheres – spherical conservatories serve as employee lounge and workspace located on the headquarters campus of Amazon company in Seattle, USA, completed in January 2018: connections details (author of photography: Manuel Bahamondez H [10])



Fig. 8. Atrium in Brookfield Place office complex, Toronto, Canada: interior view (author of photography: Marcos Virgílio [10]) and steel column base detail (author of photography: cbrueck [10])

In one design, and even in one steel element, different AESS categories may occur. It allows reasonable selection of means and methods for increasing quality and keeping additional (premium) costs to a minimum. It is estimated that premium costs are in the range from 20% for AESS 1 to 250% for AESS 4 categories compared to the SSS.

The AESS category must be clearly specified by the architect and indicated in design and execution documentation (both in the text and on the drawings).

3. Shaping and execution of joints and connections

Joints and connections are the main means of architectural expression in architecturally exposed steel structures, but they still perform their basic function that is allowing the safe transfer of loads between connected elements and enabling an efficient transport to the site and structure execution. The way of joint shaping may drastically affect the labour costs at the stage of design and detailing, manufacturing, transport, and structure execution.

The type, location and quality of joint execution should be consistent with the general aesthetic concept of the building – as a result two basic types of joint shaping may be identified: they may be displayed or hidden from the sight of the observer. Connection, and particularly splice of steel elements, is the place where the continuity of the compositional lines created by the element outlines is disturbed. These lines naturally “lead” human eye during observation of the structure and connections are the points that spontaneously focused observer’s attention. This effect can be undesirable if the essence of architectural expression are smooth lines and minimalistic forms used in different styles of modernist architecture. However, the connection may sometimes be treated as a valuable item of aesthetic effect intended by the architect, e.g. accentuating the industrial style by referring with bolts arrangement in joint to the textures of the background surfaces.

The principles of joints and connections shaping in AESS are the same as for SSS. Correctly shaped and designed joints and connections of structural elements should primarily meet the safety, serviceability and durability requirements as well as enable easy execution of the structure. Additional requirements to the expected aesthetic of the structure causes the need for reasonable methods of AESS shaping, that would allow to meet abovementioned requirements with only a little increase of costs in comparison with SSS. This can be achieved by using one of the following recommendations.

If the joint or connection is visible to the observer and harmonises with aesthetic concept of the structure, it shall be shaped in a way that refers to lines or textures of adjacent elements. If the joint or connection is meant to be “a strong point” of the composition, its elements, e.g. bolts or gusset plates, can be emphasize by increasing their number or dimensions, introducing additional holes which are unnecessary from structural point of view, designing gusset plates with more attractive geometrical shapes, e.g. curved, or manipulate colour, lighting and texture of the surface (Fig. 9).



Fig. 9. Centre Georges Pompidou, Paris, France. Visible enlarged gusset plates, additionally accentuated by the central hole (author of photography: V C [10])



Fig. 10. The joint of steel spatial structure at Heathrow airport, London, England (author of photography: Andreas Komodromos [10])

In the case of geometrically complicated joints in complex three dimensional steel structures, it often is preferable from both an aesthetic and financial point of view, to apply prefabricated cast steel elements (Fig. 10).

If the joint or connection is visible to the observer but its accentuation is inadvisable, the measures ensuring that it will minimally focus the observer's attention should be applied. These can be for example: using of welded connections instead of the bolted ones, replacing the welded shear connections with the end plate connections, replacing the intermittent fillet welds with continuous fillet welds, minimising of gaps between the connected elements, removal of welding spatters, weld grinding, surface defects supplementing with special synthetic filler, placing all bolt heads on one side of the joint, etc.

If the location of the joint in particular part of the structure is unfavourable from the aesthetic point of view, one may try to transfer it to other, less exposed place, even if for design or execution reasons it will be a worse location. The location of hollow section longitudinal seams on the side which is non-visible to the observer may be the example. If the joint cannot be transferred, one may try to hide it by appropriate shaping. In this case two approaches may be distinguished. The first one is to hide the joint by such gusset or end plates shaping that they are practically within the contour of connected profiles. The joint can be additionally enclosed by non-structural cover plates in the shape of a connected profile. The second approach involves the use of cast steel elements welded to the connected profiles. After assembly, bolt heads and nuts are hidden in hollows of the cast that are later filled in with weld deposit and ground.

If this is consistent with the aesthetic concept of the structure, some of the welded joints can be replaced by bent elements. It can be applied in the case of both connections of straight elements that form curved element and the gusset plates.

4. Summary

The high yield strength of steel makes it possible to erect building structures with slender elements, which only minimally limit the access of natural daylight to the interiors. At the same time, exposed steel structural elements became the means of the architectural expression. Joints and connections, as inherent part of steel structure, also began to be a subject of architectural design. They are an essential component of steel structure visual appearance, being within the observer's sight. Due to the fact that the fulfilment of the architect aesthetic expectations requires an increase effort, both at the stage of design and execution, AESS can be significantly (even a few hundred percent) more expensive than SSS with exactly the same functionality and durability. It should be noted that greater part of additional costs is associated with joint execution, that must meet quality requirements much higher than these for standard steel structures.

The current standard for execution of steel structures PN-EN 1090-2 [7], does not refer to execution of AESS. In the case of incorrect or incomplete specification of steel structure, it may be an obstacle to the mutual communication between the architect, engineer and contractor. This leads to misunderstandings that may sometimes have serious consequences, e.g. financial – resulting from the necessity to redesign or re-execution of structural parts, which is often associated with delays in termination of the investment. The possibility of such situation may cause that the investor will treat the realization of architecturally exposed steel structures as a venture of higher financial risk what may limit the application and development of AESS. Therefore, the demand for actions aimed at the introduction to current standard PN-EN 1090-2 [7] provisions about the execution of architecturally exposed steel structures seems to be justified.

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