WARSAW UNIVERSITY OF TECHNOLOGY | Index 351733 | DOI: 10.24425/ace.2025.156180

FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING

ARCHIVES OF CIVIL ENGINEERING

POLISH ACADEMY OF SCIENCES | ISSN 1230-2945 | Vol. LXXI | ISSUE 4 | 2025

pp. 441 –449

Research paper

Safety issues related to the use of closed profiles in steel girders

Marcin Górecki[1], Małgorzata Snela[2], Ewa Błazik-Borowa[3], Anna Halicka[4]

Abstract: This paper analyses the stress state in the walls of a closed steel profile caused by freezing water filling the interior of the profile. The study focuses on a specific case of two damaged girders, where the failure was attributed to freezing water trapped inside the upper chords of the girders. The analysis revealed that the resulting stresses exceeded the steel's strength, leading to deformation and rupture of the upper chord profiles. The article describes the damage observed in the girders, including outward deformation of the walls and cracks along the bending edge. The presence of water and corrosion products inside the profiles was confirmed through inspections. Finite element calculations were performed to assess the pressure effects, showing that the tensile stresses in the corner of the profile exceeded the yield and tensile strength of the steel. The article concludes that damage caused by freezing water expansion is unpredictable and emphasises the importance of weld quality control in steel structures.

Keywords: closed profile, deformation, FEM calculations, freezing water, steel structures, stresses

[1]PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, 40 Nadbystrzycka Street, 20-618 Lublin, Poland, e-mail: m.gorecki@pollub.pl, ORCID: 0000-0001-8746-8172
[2]PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, 40 Nadbystrzycka Street, 20-618 Lublin, Poland, e-mail: m.snela@pollub.pl, ORCID: 0000-0003-0210-4965
[3]Prof., DSc., PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, 40 Nadbystrzycka Street, 20-618 Lublin, Poland, e-mail: e.blazik-borowa@pollub.pl, ORCID: 0000-0001-8200-3827
[4]Prof., DSc., PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, 40 Nadbystrzycka Street, 20-618 Lublin, Poland, e-mail: a.halicka@pollub.pl, ORCID: 0000-0001-5526-8862

1. Introduction

The objective of this article is to analyse the stress state in the walls of a closed steel profile generated by freezing water filling the interior of the profile. The analysis refers to a specific case of two damaged girders, where a periodic inspection of the building's steel structure revealed unusual damage to the upper chords. A detailed inventory of the structure, conducted by the authors, led to the hypothesis that the failure resulted from freezing water trapped inside the upper chords of the girders. The analysis revealed that the resulting stresses exceeded the steel's strength and were responsible for the deformation and rupture of the upper chord profiles. A similar case of damage to tubular profiles was described in [1]. Damage caused by freezing water inside steel structures is also observed in bridge structures [2].

In the discussed case, the girders were made of cold-formed tubular profiles of steel grade S355J2. Both the upper and lower chords of the girders, laid with a slope, were made from square tubes with a seam and an external wall dimension of 200 mm. The profiles used for the girder chords differ in wall thickness. For the upper chords, RK200 with a wall thickness of 6 mm or 5 mm was used, while for the lower chords, RK200 profiles with wall thicknesses of 4 mm, 8 mm, or 10 mm were used. Both girder columns and bracings were made from RK120 tubular profiles with varying wall thicknesses of 4 mm, 5 mm, or 6 mm. The girders were hinged to reinforced concrete columns in the upper and lower chord horizontally and also suspended from the columns using tie rods made of round tube profiles RO 108×10 (Fig. 1). The tie rod attachment to the upper chords of the girders was facilitated through a 25-mm-thick junction plate. Corrosion protection, involving external paint coatings, requires airtight closure of the profiles [3].

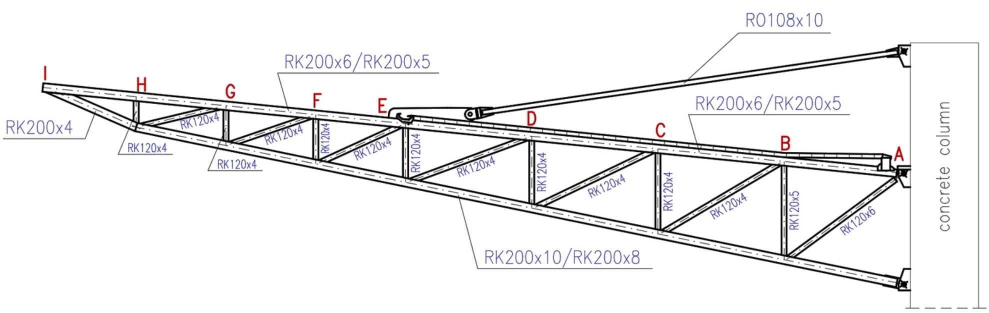

Fig. 1. Diagram of the damaged truss girder – upper chord made of square tube RK200

2. Girder damage

In the first damaged girder, deformation of the cross-sectional shape of the upper chord profile was observed – walls were "pushed out" outward over a length of four consecutive spans from A to E (Fig. 2). These deformations were sectional, occurring along the sections of the chord between successive nodes. In the nodes, the section is "constrained": in the plane of the girder by columns and bracings, out of the plane by node plate stiffeners.

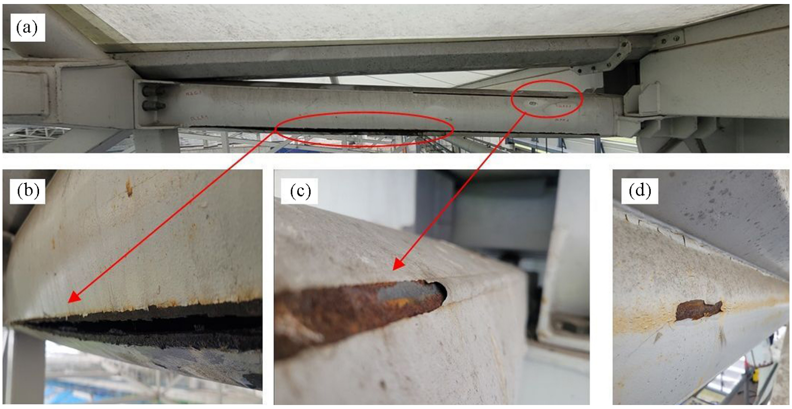

Fig. 2. Deformation of the tubular profile of the first of the inventoried girders and damages caused by deformations: (a) view of the end span AB of the upper chord, (b) crack along the lower edge of the bend, (c) chipping of the paint coating and corrosion on the upper edge of the bend, (d) cracks and chipping of the paint coating on the wall BC section profile

A continuity loss of the upper chord profile material was also found in the extreme span as a crack along its lower bend edge (Fig. 2b). This crack was approximately 950 mm long and about 12 mm wide at its widest point. Water seeped from the crack, revealing signs of corrosion on the tube's inner surface. Swelling of the paint coating was observed on the profile edge (Fig. 2c) and peeling of the paint layers on the side walls was noted (Fig. 2d).

Using the damage in the form of the profile rupture, an inspection of the upper chord profile interior was conducted using a Mitcorp Prelude videoendoscope. The inspection confirmed the presence of water and algae in the profile. The water level was determined during the inspection to be reaching the lower end of the crack section. Corrosion products were found on the internal surfaces of the tubular element walls, and loose corrosion products were observed on the lower surface of the profile wall, indicating a significant degree of corrosion of all profile walls (Fig. 3).

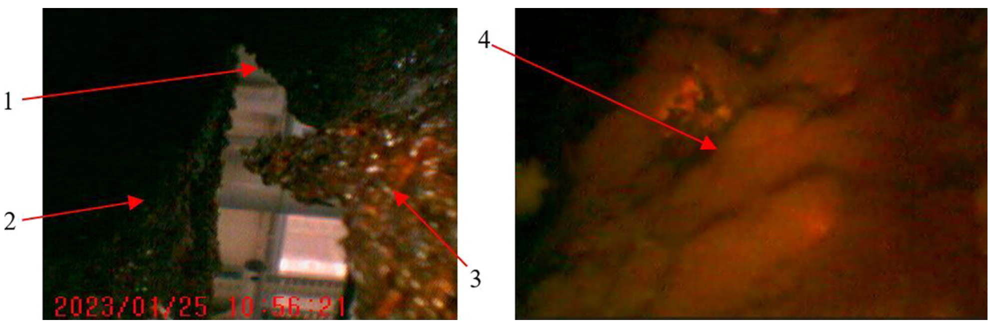

Fig. 3. Interior image of the upper chord obtained via videoscope: 1 – crack, 2 – rust, 3 – loose corrosion products, 4 – algae in the water retention zone

The second damaged girder also exhibited outward deformation of its walls (Fig. 4) over several spans. Similar to the first girder, these deformations were segmental, appearing over the length of the chord sections between successive nodes. Paint coat flaking was observed along the bending edge and weld seam of the tube, with corrosion visible at these points.

Fig. 4. Deformation of the tubular profile of the second damaged girder

In the second damaged girder, similar to the first, a crack in the upper chord profile was found in the extreme span along the upper bend edge (Fig. 5a). Water was visible through the crack, flowing out and streaming along the side and bottom walls of the upper chord (Fig. 5b).

(a) (b) (c)

Fig. 5. Damage to the second girder caused by deformations: (a) crack along the upper bend edge, (b) paint coating flaking and corrosion on the lower bend edge, (c) inventory of wall deformations

Seeking the water ingress point, a discontinuity was found in the butt weld connecting the node plate used for rod attachment to the upper chord surface (Fig. 6) at node E (Fig. 1). Water penetrated through this discontinuity into the upper chord, flowing down its slope to the extreme span, then filled the entire section and froze, causing the described damage. The described weld discontinuity is a welding non-conformity in the form of a crater at the end zone of the node plate. At this point, the plate used for rod attachment passes through the upper chord walls. The crater was likely due to improper weld termination during the welding process, possibly related to a sudden power cut-off and arc extinguishment.

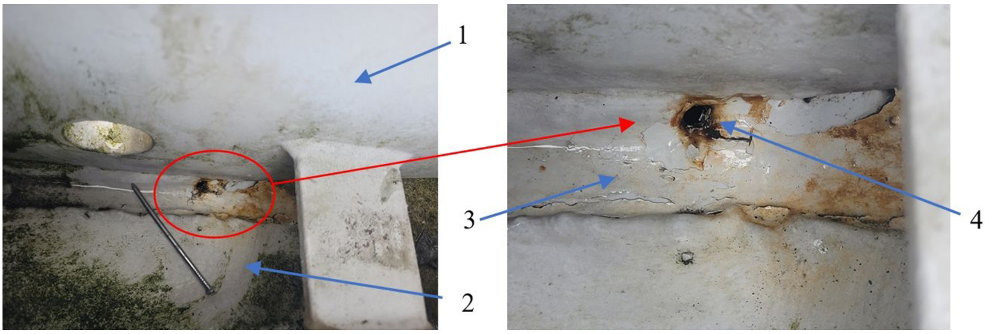

Fig. 6. Discontinuity of the weld connecting the gusset plate to the upper chord of the girder: 1 – gusset plate, 2 – upper surface of the upper chord, 3 – fillet weld, 4 – crater

3. Damage mechanism – numerical analysis

The damage to the girders, specifically their upper chords, manifested as follows:

– Cracking of the tubular profile over a nearly 1-metre length along the bending edge (top or bottom),
– Outward deformation of the walls of the tubular profile (Fig. 4) in regions where the upper chord, sloped towards the support, has its lowest position; the deformations of all walls were uniform and plastic – they did not revert after pressure release.

The pressure resulted from the freezing water inside the profile. The inspection confirmed the presence of water reaching almost the upper edge of the cross-section in the lowest part of the chord of one of the girders, with water leaking from the profile observed during the on-site inspection.

To assess the pressure effects, finite element calculations were performed (Autodesk Algor Simulation 2011 [4]). A 1-metre section of a 200 × 200 × 6 cold-formed square tube was modelled and subjected to increasing internal pressure. The model is shown in Fig. 7. Shell elements modelling the pipe surface were inserted in the middle of the wall thickness. Elastic-plastic material model calculations were used, with a yield strength $f_y = 355$ MPa and a tensile strength $f_u = 490$ MPa, corresponding to S355 steel according to EC3 [5]. Based on the plasticity criterion, the material followed the plastic flow law and the kinematic hardening law. Additionally, a Young's modulus value of $E = 2.10 \cdot 10^8$ kPa and a hardening modulus of $E_t = 0.01 \cdot E$ were assumed [6].

Figure 8 shows the calculated dependence of the tensile stresses in the tubular profile on its bent edge and the internal pressure. It shows that the tensile stresses in the corner exceed the yield strength at approximately 1.2 MPa and the tensile strength at approximately 4.6 MPa. This actually happened: upon reaching tensile strength, a crack occurred in the corner at the bend edge.

Figure 9 shows the stress state maps in the section under the load indicated by points A and B in Fig. 8. Uncoloured (white) elements are visible, where stresses exceed either the yield strength or the tensile strength. These areas correspond to the corners where the crack occurred.

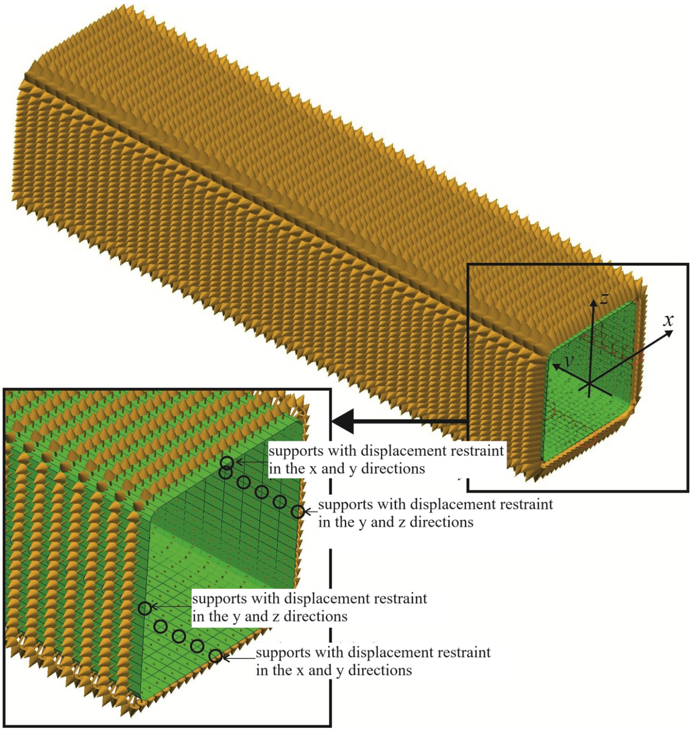

Fig. 7. Numerical model of a rectangular tube with pressure loading and supports

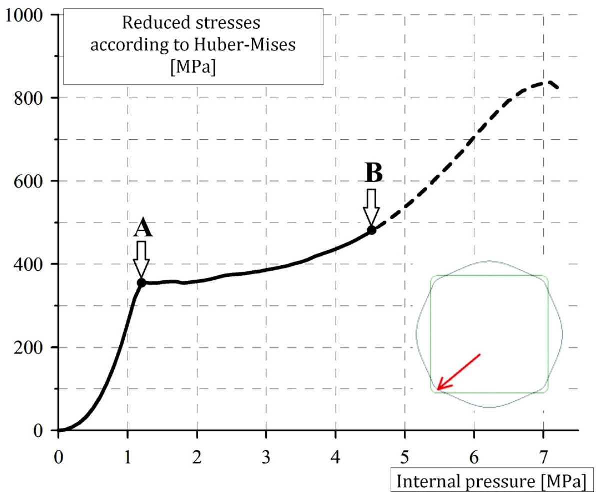

Fig. 8. Relationship between reduced stresses at the profile edge and internal pressure

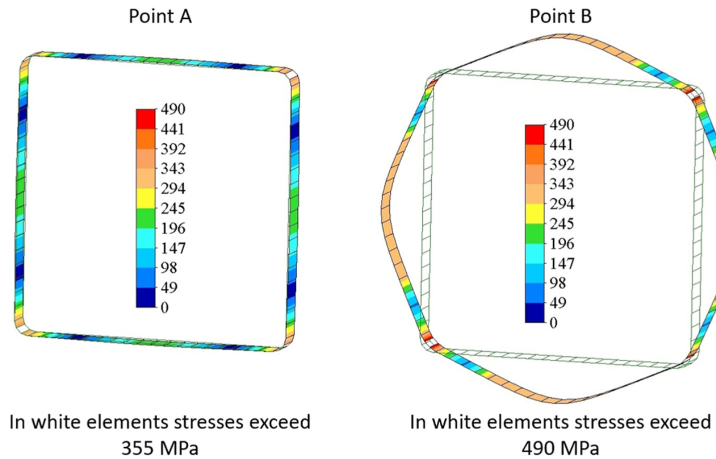

Fig. 9. Stress maps in the tubular section under different loads

As a result of the calculations, a correlation between the wall displacement and the internal pressure obtained at the corner and at the midpoint of the wall was established, which is shown in Figure 10. It was found that stresses equal to the characteristic tensile strength of steel correlated with a wall displacement in the central part of about 10 mm. The deformation observed in situ was greater. This can be attributed to the fact that the actual corner strength could be higher (the bending effect and the characteristic strength are the 95‰ quantile of test results), and the mechanism could involve cyclic freezing and thawing of the water inside, changing the conditions of subsequent deformations. Freezing water after a profile rupture could lead to further deformation and crack widening.

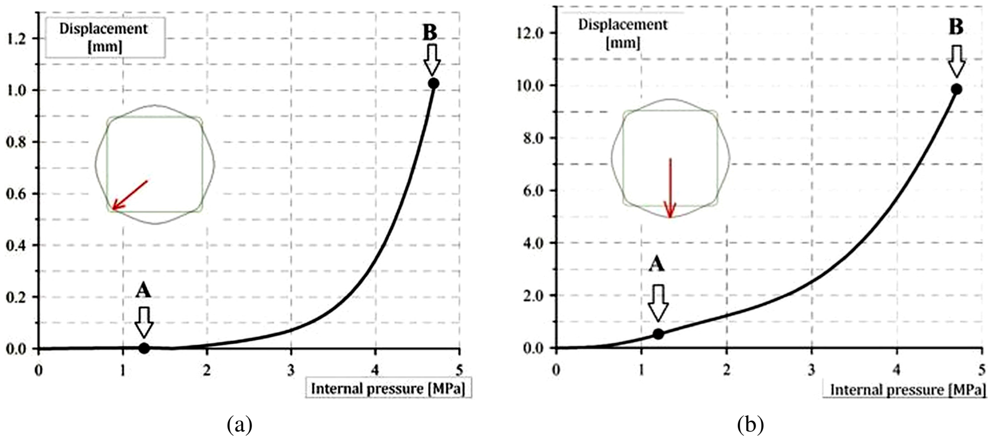

Fig. 10. Correlation between wall displacement and internal pressure in a $200 \times 200 \times 6$ tubular profile: (a) at the corner, (b) at the midpoint of the wall

Water increases its volume by approximately 9% when it freezes. The measured values indicate a greater volume increase. The cross-sectional area inside the analysed square tube was 353.36 cm^2 before deformation and 429.39 cm^2 after deformation, resulting in a 21% increase. This confirms the hypothesis that between successive freezing cycles, the amount of water entering the tube increased.

4. Damage mechanism – numerical analysis

The conducted analysis resulted in the following conclusions:

– If water can penetrate the interior of a closed profile, damage can occur due to the pressure exerted by freezing water and the expanding ice volume,
– Damage to closed profiles in the form of cracking leads to a reduction in the steel wall thickness due to an accelerated corrosion process caused by the ingress of oxygen and water, and consequently a reduction in the wall stability under compressive loads,
– Deformations on the external surfaces of the profile walls, resulting from tensile stresses on the flat wall surface and compressive stresses on the bend edge, contribute to paint coatings damage (low deformability) through cracking or peeling, leading consequently to steel corrosion,
– Damage to closed profiles results in changes to geometric characteristics, particularly the opening of the profile, which significantly reduces torsional stiffness,
– Damage caused by freezing water expansion is a type of damage that cannot be predicted by designers,
– The presented example highlights the importance of weld quality control in steel structures.

Acknowledgements

This research was supported by the Lublin University of Technology Science Financing Subsidy FN-4/2023.

References

[1] D. Kowalski, “Corrosion and destruction of steel hollow sections”, Przegląd Budowlany (Builders Review), no. 5, pp. 32–34, 2016 (in Polish).

[2] M. Kulpa, D. Sobala, and T. Siwowski, “ Failure analysis and repair method assessment for a steel box girder bridge”, in *XXVIII Konferencja Naukowo-Techniczna “Awarie budowlane” Szczecin – Międzyzdroje, 2017*. Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, 2017, pp. 1027–1038 (in Polish).

[3] J. Bródka and M. Broniewicz, *Steel structures made of tubes*. Warszawa: Arkady, 2001 (in Polish).

[4] Autodesk Algor Simulation, 2011.

[5] PN-EN 1993-1-1 Eurokod 3: Projektowanie konstrukcji stalowych. Część 1–1: Reguły ogólne i reguły dla budynków. PKN, 2006.

[6] PN-EN 1993-1-5 Eurokod 3: Projektowanie konstrukcji stalowych. Część 1–5: Blachownice. PKN, 2008.

Niebezpieczeństwa związane ze stosowaniem profili zamkniętych w dźwigarach stalowych

Słowa kluczowe: analiza MES, deformacje, element stalowy, naprężenia, profil zamknięty, zamarzanie wody

Streszczenie:

Celem niniejszego artykułu jest analiza stanu naprężeń w ścianach stalowego profilu zamkniętego, generowanych przez zamarzającą wodę wypełniającą wnętrze profilu. Rozważono konkretny przypadek dwóch dźwigarów, w których podczas okresowego przeglądu stwierdzono uszkodzenia pasów górnych. Postawiono tezę, że przyczyną awarii była zamarzająca woda, która dostała się do wnętrza pasów górnych dźwigarów. Dźwigary wykonane były z zimnogiętych profili rurowych ze stali gatunku S355J2. Pasy górne i dolne dźwigarów wykonano z rur kwadratowych ze szwem o różnej grubości ścianek. Słupki i krzyżulce zostały wykonane z profili rurowych o różnej grubości ścianek. Dźwigary były zamocowane przegubowo do słupów żelbetowych i dodatkowo podwieszone do tychże słupów za pomocą cięgien z profili rurowych. W obu uszkodzonych dźwigarach zaobserwowano deformację kształtu poprzecznego profilu pasa górnego oraz pęknięcie wzdłuż krawędzi gięcia. Wziernikowanie wnętrz profili potwierdziło obecność wody i glonów. Stwierdzono również nieciągłość spoiny czołowej w węzłach łączących pas górny dźwigarów z cięgnami, przez którą woda wnikała do wnętrza pasów górnych tych dźwigarów i powodowała uszkodzenia. Przeprowadzono analizę numeryczną, aby ocenić efekty działania ciśnienia wywołanego przez zamarzającą wodę. Obliczenia wykazały, że naprężenia rozciągające w narożach przekraczały granicę plastyczności i wytrzymałość na rozciąganie. Analizowano również przemieszczenia ścianek profilu w zależności od ciśnienia wewnętrznego. Stwierdzono, że naprężeniom równym wytrzymałości stali towarzyszyło przemieszczenie ścianek w centralnej części profilu. Wnioski z przeprowadzonej analizy wykazały, że jeśli woda ma możliwość wniknięcia do wnętrza profilu zamkniętego, może dojść do uszkodzenia spowodowanego ciśnieniem wywieranym przez zamarzającą wodę. Uszkodzenie profili prowadzi do zmniejszenia grubości ścianek, obniżenia stateczności i zmiany charakterystyk geometrycznych. Uszkodzenia te są trudne do przewidzenia przez projektanta. Kontrola jakości spoin w konstrukcjach stalowych jest ważna, aby zapobiec tego rodzaju uszkodzeniom.

Received: 2024-07-08, Revised: 2024-08-06