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Influence of fatigue load on bearing capacity of STEEL PLATES IN bolted connections.

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Introduction

Many of currently used steel structures are very old, but due to their historical nature, it is worth keeping them in a good state of repair, as they constitute an important element of our history and cultural heritage. These structures often require intervention in form of reinforcement or modifications connected with their adaptation to the binding regulations and usage-related requirements. As most of historical types of steel are non-weldable, all repairs must be conducted with use of bolted connections. Apart from non-weldable steel that completely excludes the possibility to join elements with use of welding, there are also weldable types of steel whose mechanical properties may be deteriorated as a result of local overheating. The factors that affect it include, among others, the manufacturing process of such steel. The St3M carbon steel that is widely used in bridge construction has good welding parameters if it has been manufactured in Simens-Martin furnaces, but it loses its properties when cast with use of the Thomas method and it becomes very sensitive to "cold" processing. Due to high phosphorus content, it is prone to brittle cracking, in particular when subjected to dynamic loads, which occur quite frequently in bridge structures [4]. Old structures often do not have any archived documentation that would contain detailed data at least concerning the materials used to erect them. This always hinders designing with use of such elements. Such designs should always be prepared very carefully, because the influence of long-term operation of the structure, apart from the obvious wear and tear, e.g. corrosion, also changes the mechanical properties of the structural material. This requires the designer to use such ways to modify the existing structure that will not expose it to additional damages caused by incorrect technological processes. Due to the above, it seems reasonable to use bolts to connect elements in existing structure. Much easier technology of preparing bolted connections in-situ and the fact that their quality will more likely be high are strong arguments supporting the use of such solution.

However, designers may face the issue how to determine the bearing capacity of such connection that was constructed with use of new connecting elements and "old" sheets of metal. It is particularly important to determine the mechanical properties of the material in the connected that was constructed with use of new connecting elements and “old” sheets of metal. It is particularly important to determine the mechanical properties of the material in the connected elements, in which, for example, a significant part of the bearing capacity was used due to fatigue.

In order to determine the influence of fatigue on the bearing capacity in bolted connections, the authors of this paper used samples collected from elements of a railroad bridge that had been in use for approx. 70 years. The structure of the bridge consisted of two T-girders braced to each other. The theoretical span of the bridge was L_t =13.48 m. The double T-girders of a height h=1.2 m, chords of a width of approx. 300 mm and a varied thickness along the length of the bridge, from 16 mm above the bridge support to 28 mm in the span of the bridge. The view and the basic dimensions of the bridge structure are shown in Figures 1 and 2.

Figure 1. View of the bridge before disassembly.

The bridge was located at 13.110 km of railroad line No. 81 between Chełm and Włodawa, in the eastern part of Poland, near the Ukrainian border. Line 81 was constructed in 1887, for military purposes. Over time, its nature has changed. Currently, the railway line is being reactivated. In the future, it will operate both passenger and freight transport. Data made available by the Polish State Railways show that in the period when the analysed object was a part of the railway line, it operated freight transport - four trains a day. This gives a total of approx. 160 000 trains crossing the discussed bridge.

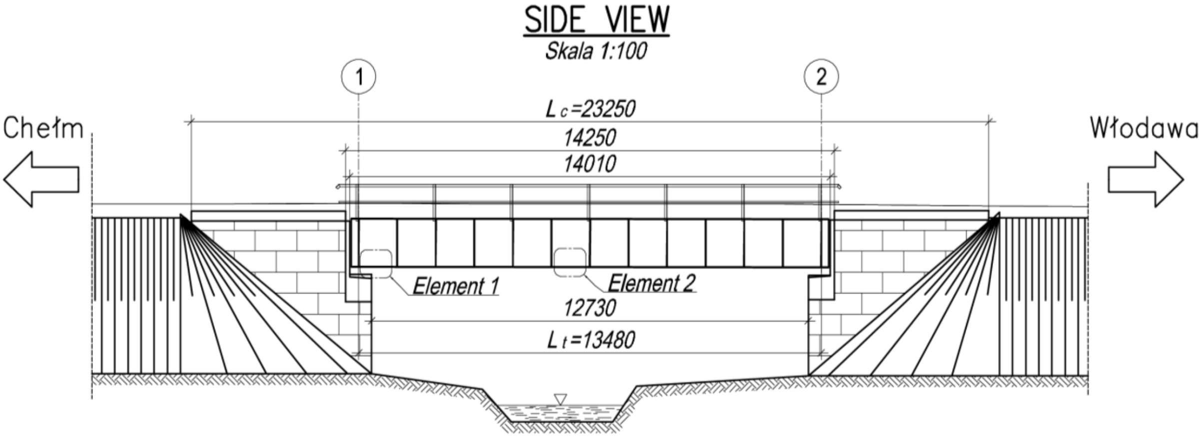

Figure 2. Drawing of the bridge with main dimensions.

Methodology of the tests

The conducted research involved static tensile strength tests of steel conducted on samples collected from bridge elements. The aim of the test was to assign the analysed type of material to a specific strength category. These tests enable to determine the specific modulus (Young modulus), yield strength of steel (R_e) and its tensile strength (R_m) [4]. Samples were cut out with use of a numerically controlled machine that uses a stream of water for cutting. This is the best method, as it prevents the influence of temperature during the preparation of samples. Samples were prepared in compliance with the guidelines provided in PN-EN ISO 6892-1:2010. The dimensions and shape of the samples are shown in Figure 3. Samples were collected from the web of the analysed elements. The location of samples used for tests is shown in Figure 4.

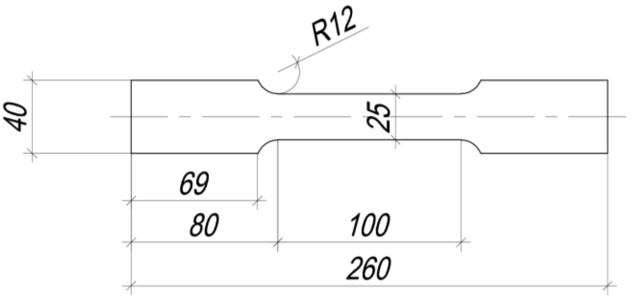

Figure 3. Sample for strength testing, prepared in compliance with the guidelines of the PN-EN ISO 6892-1:2016-09 standard.

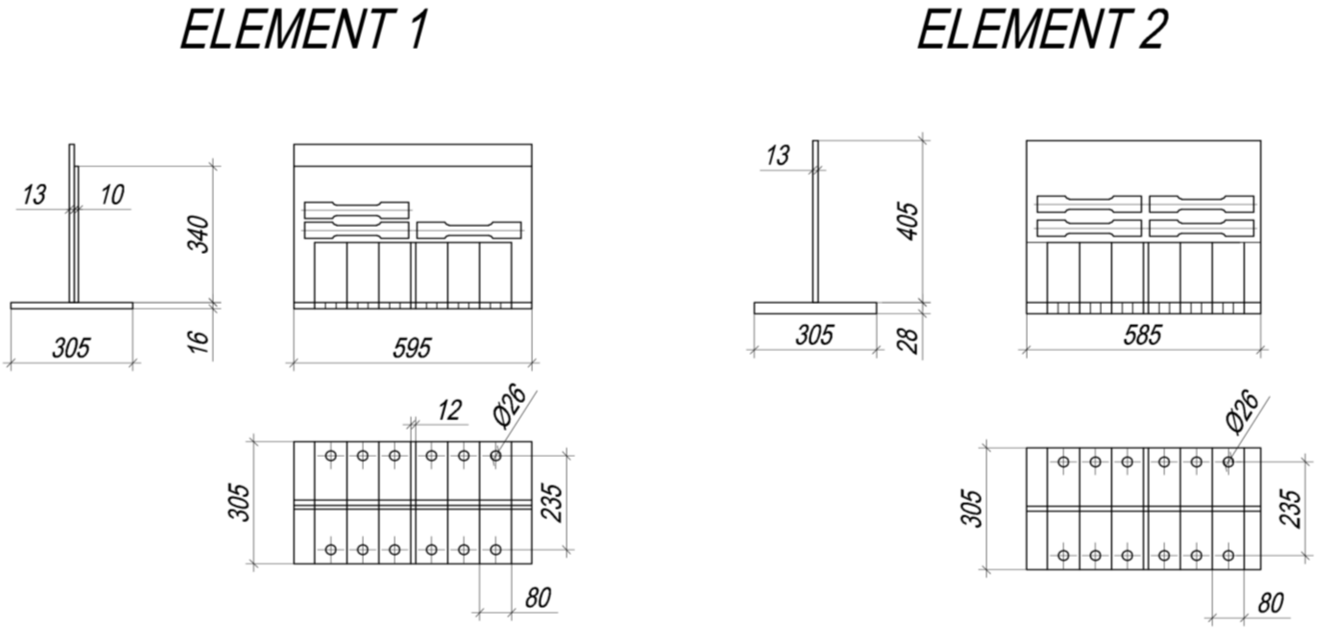

Figure 4. General view of placing the samples on element.

Samples for the bearing capacity tests of bolted connections were T-shaped. The endplate of the connection was a belt of the main girder of the bridge. Due to the simply supported beam design, element 2 cut out from the middle section of the bridge span was the element exposed to the highest influence of fatigue load. As a result, analyses of this element are even more valuable, as they demonstrate the influence of fatigue on the bearing capacity of the newly designed connection, which uses elements of the existing structures. The Authors previously analysed the influence of long-term fatigue load on the bearing capacity of structural elements and the possibility to operate it safely [2], [3]. Samples collected from element 1 will serve as reference samples for the determination of the influence of fatigue on bearing capacity.

Results of tensile strength tests

In order to verify the type of steel and the influence of fatigue on its basic characteristics, static tensile strength tests were conducted. As a result of the conducted tests it was determined that the steel is characterised by a yield strength fy of approx. 300MPa, and a tensile strength of approx. 450 MPa. This means that this is a very strong type of steel, whose properties are much better than those of S235 steel. Tables 1 and 2 below present the results of tensile strength tests of steel from elements 1 (Table 1) and 2 (Table 2). Figures 5 and 6 show the diagrams of the σ-ε correlation for the analysed samples.

Table 1. Basic mechanical properties of steel determined in the tests of samples collected from the element 1.

Sample No.	R_m	R_{eL}	R_{eH}	R_z	ε_{max}
	MPa	MPa	MPa	MPa	mm/mm
N-1	450	285	308	330	0.3203
N-2.	452	325	304	321	0.3156
N-3	446	287	330	318	0.2961
MIN	446	285	304	318	0.2961
MAX	452	325	330	330	0.3203
Average	449	299	314	323	0.3107
Standard deviation	3	23	14	6	0.0129
Coefficient of variation	1%	8%	4%	2%	4%

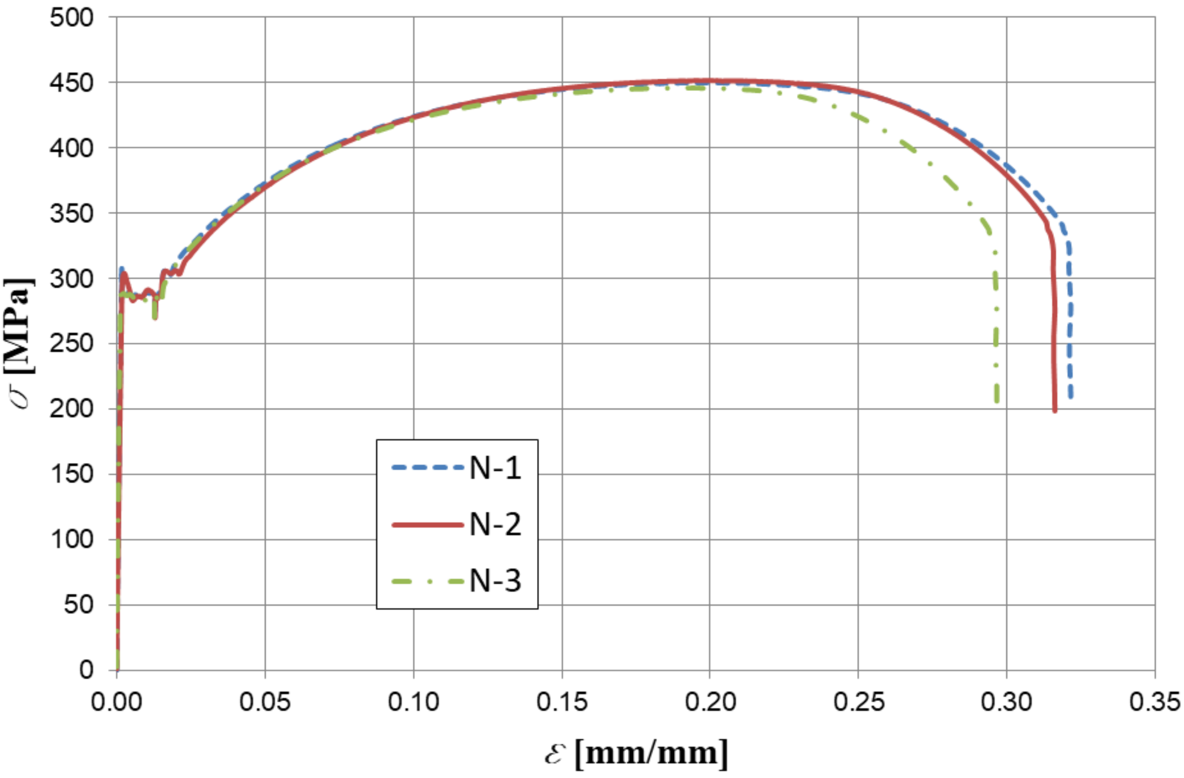

Figure 5. Diagram of the strain-deformation relation for samples cut out from element 1.

Table 2. Basic mechanical properties of steel determined in the tests of samples collected from the element 2.

Sample No.	R_m	R_{eL}	R_{eH}	R_z	ε_{max}
	MPa	MPa	MPa	MPa	mm/mm
Z-1	449	281	295	318	0.3212
Z-2	447	274	293	324	0.3279
Z-3	444	272	284	324	0.3326
Z-4	445	284	289	324	0.3340
MIN	444	272	284	318	0.3212
MAX	449	284	295	324	0.3340
Average	446	278	290	323	0.3289
Standard deviation	2	6	5	0	0.0032
Coefficient of variation	0%	2%	2%	0%	1%

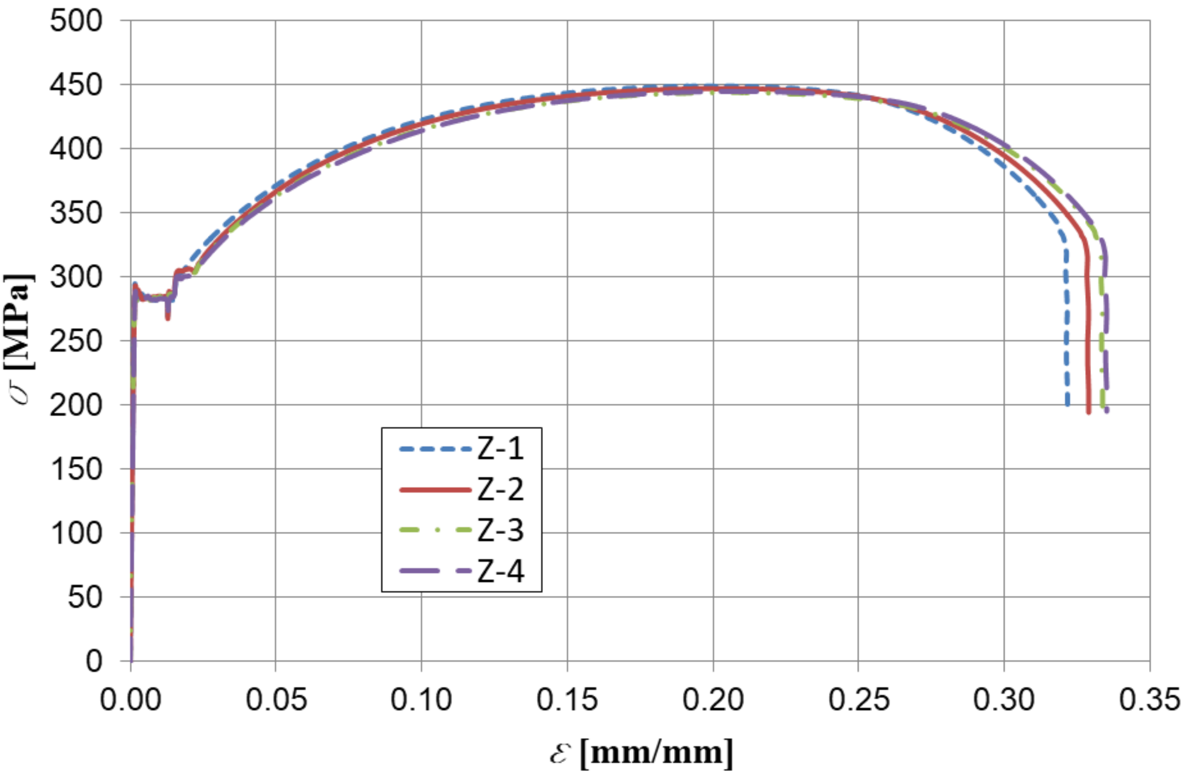

Figure 6. Diagram of the strain-deformation relation for samples cut out from element 2.

The presented results lead to a conclusion that the strength characteristics of steel collected from the bridge span are much lower than those of samples collected from above the bridge support. For the yield strength f_y this influence equals 8%. As far as tensile strength is concerned, this influence is lower and the difference is only 1%.

Results of finite element method analysis

Then, a numerical model was created of a bolted connection analogical to the one that was later analysed experimentally. The non-linear characteristics of the material used were consistent with those of experimental test results. The application of RFEM software enabled us to implement a detailed characteristics of steel strength diagram. The geometry of the numerically analysed connection did not take into account the corrosion cavities that existed in elements used in experimental tests. Figure 3 shows the view of a bolted connection deformed as a result of tensile load, respectively, view a) shows the connection of 16 mm endplates and view b) the connection of

28 mm thick endplates. The aim of the numerical analyses was to obtain such shape of the connection in geometrical terms and such selection of connectors that would result in the endplates being destroyed during the tensile strength test as a result of the developed yield. Such destruction was important due to the aim of the conducted research, which was to determine the bearing capacity of elements constructed from the materials of an already existing object.

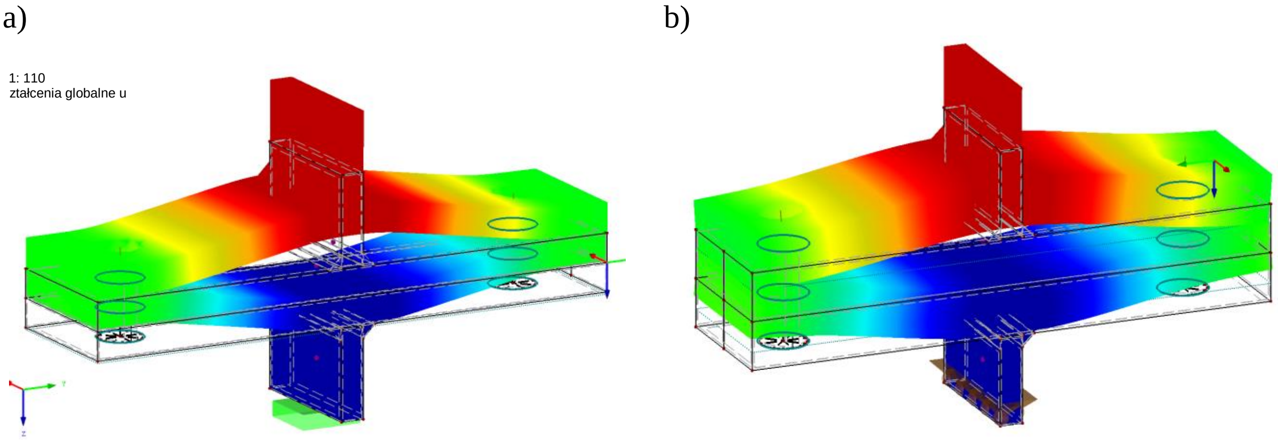

Figure 7. Diagram of the deformation of bolted connection – RFEM analysis, a) endplate 16mm; b) endplate 28mm

The diagram below (Fig. 8) shows the dependence of the relation between force and deformation for a bolted connection with 28 mm endplate. Similar calculations were also performed for the connection with a 16 mm endplate.

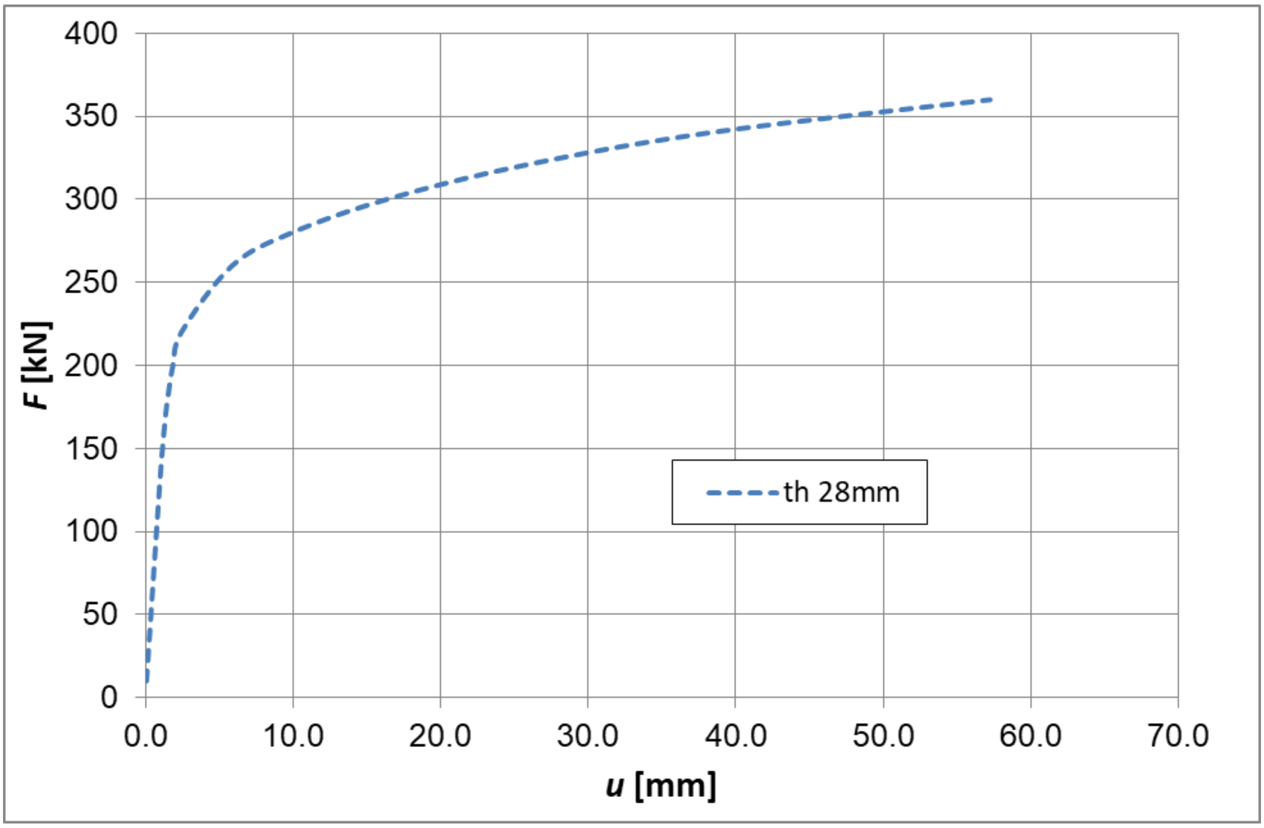

Figure 8. Diagram of the force-deformation relation for connection with 28mm endplate.

Results of tensile strength tests of bolted connection

The experimentally analysed connections were constructed from two T-shaped samples joined with use of two bolts of a diameter of 24 mm. Depending on the thickness of the connected elements, 12.9 class bolts were used (connection with 28mm endplates) and 8.8 class bolts (for 16 mm endplates). The selected classes of bolts were based on the results of the numerical analysis, which determined the maximum axial forces that would exist in the bolt while stretching the connection. Figure 9 shows the analysed connection in the test apparatus during tensile strength test. It is noticeable that the model of destroying the connection by bending the endplates was achieved. 3 connection of each element were analysed during the tests.

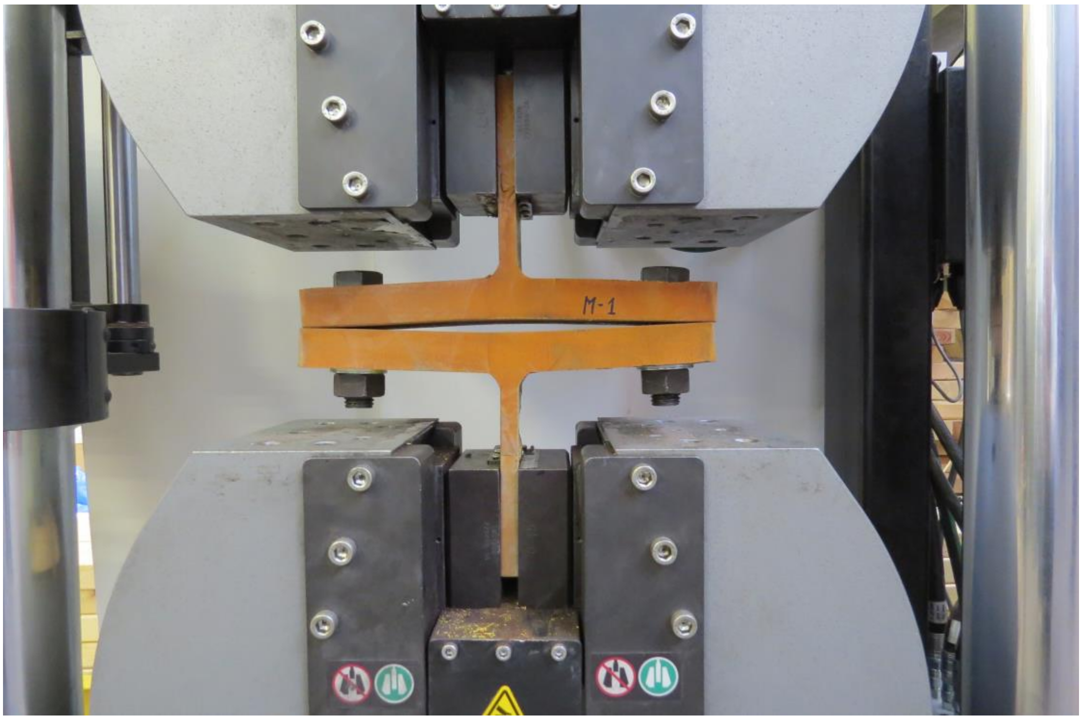

Figure 9. View of a bolted connection during tests in the Instron strength test apparatus.

Figures 10 and 11 show diagrams that illustrate the correlation between force and deformation for all the analysed connections. The diagram presented in Figure 10 shows the results of laboratory tests for samples collected from element 1.For comparison purposes, the diagram also contains a line representing the numerical results obtained in the software for finite element method analysis. The convergence of the obtained results is satisfactory. The course of force-deformation curves is very similar for all samples and for the numerical analysis results. This confirms that the applied numerical model is correct.

The diagram in Figure 11 shows the results obtained for samples collected from element 2. In this case the results of numerical analyses have also been added. One may notice that the divergence is quite significant although the same calculation procedure was used, i.e. the model corresponded to the analysed element and the material characteristics obtained from samples subjected to tensile strength tests were implemented. The difference between the bearing capacity obtained in numerical analyses and that resulting from laboratory tests is approximately 12%, which means that the actual connection bearing capacity is considerable lower than the bearing capacity determined by the numerical model.

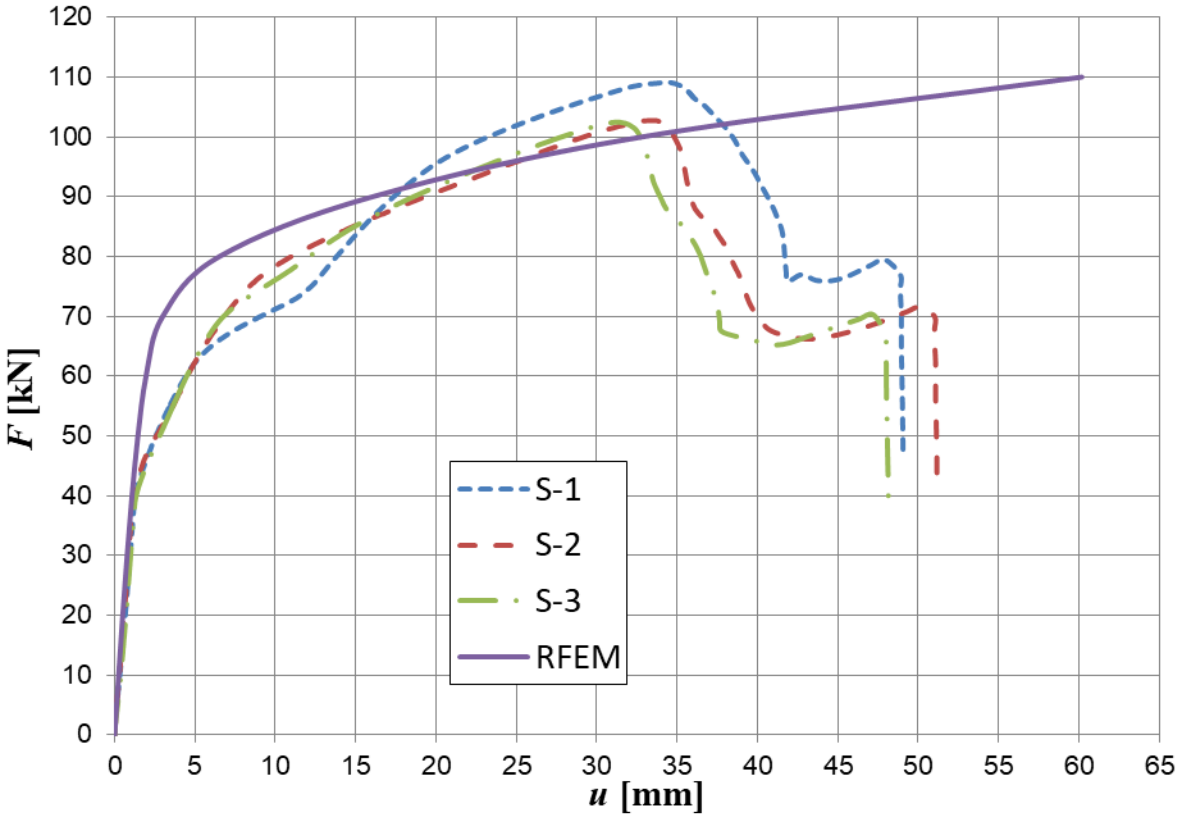

Figure 10. Diagram of the strain-deformation relation for samples cut out from element 1.

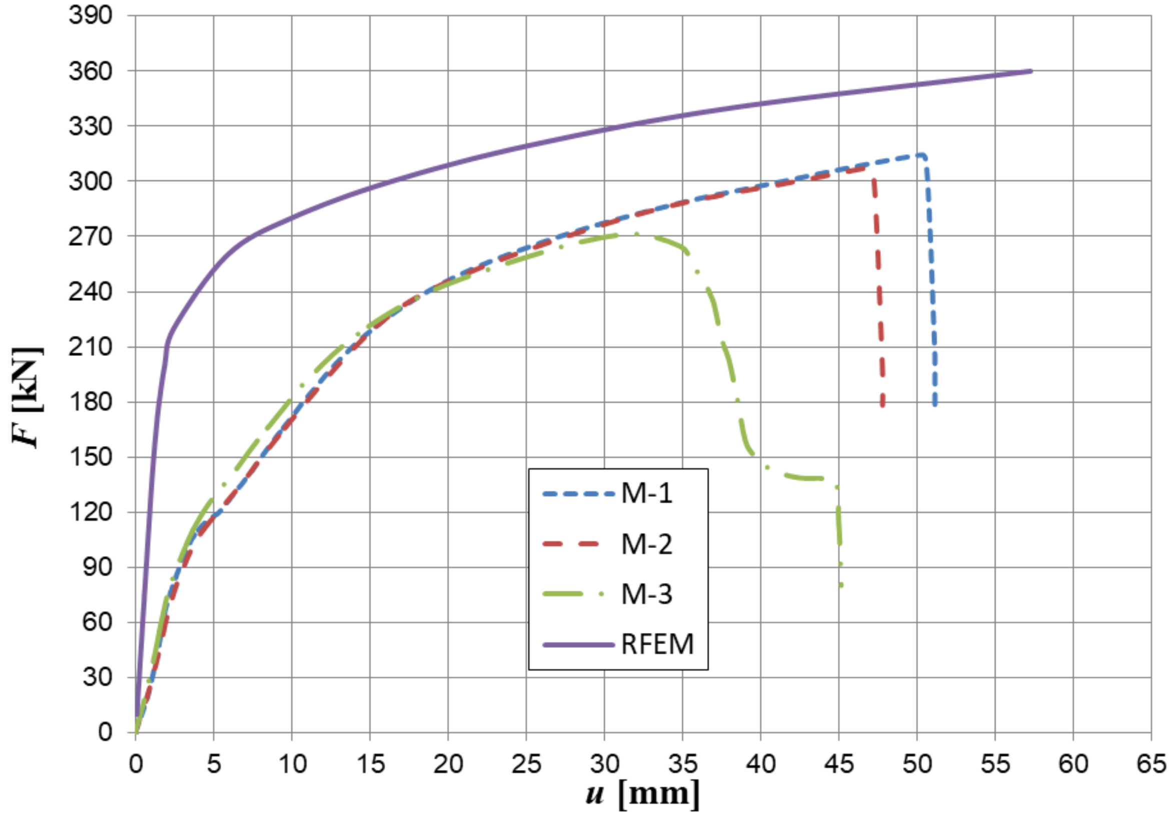

Figure 11. Diagram of the strain-deformation relation for samples cut out from element 2.

Conclusions

The conducted research consisted in static tensile strength tests of steel samples collected from the main girders of a railroad bridge that had been used for many years. It is estimated that it had been subjected to a load of approx. 160 000 trains during that time. Steel from bridge elements was used to construct bolted connections that were then subjected to static tensile strength tests. In order to compare the actual bearing capacity of the bolted connection constructed from bridge steel with the theoretical bearing capacity, a calculation model was created in the RFEM software.

The conducted analyses demonstrate that:

- The value of yield strength of steel collected from element 2 (middle of the span) analysed in the static tensile strength test is approximately 8% lower than that of steel collected from element 1 (support zone – low fatigue influence). This confirms the reduction of strength parameters of steel as a result of fatigue.
- The bearing capacity of samples cut out from element 2 is approx. 12% lower than that determined analytically with use of software.
- The bearing capacity of connection constructed from elements not affected by fatigue determined in laboratory tests is convergent with the bearing capacity of a similar connection calculated with use of numerical analysis.

The above leads to the conclusion that connections constructed in existing structures with use of the existing steel elements that were previously subjected to fatigue loads should be treated with a high dose of uncertainty and that their bearing capacity should be limited for safety purposes. This conclusion is very important due to frequent attempts to introduce modifications to existing steel structures. In case when new connections are added to existing structure, they should be placed in areas of the structure where influence of fatigue loads was minimal. Operation on existing constructions can be classified as difficult engineering because often we do not have sufficient data for design. Therefore each time it is necessary to collect as much data as possible. Most important are static schemes, the history of the applied load and the material properties from which the construction was made. All doubts should be explained at the design stage and confirmed, if it is necessary, by research.

The issue discussed in the paper requires further research in order to determine the exact influence of fatigue on the bearing capacity of connections and to provide specific guidelines for designers.

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