Stress-strain behavior of welded joints in railway girders

Напряженное состояние сварных узлов железнодорожных пролетных строений

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Abstract. A metal construction with welded joints often fails under repeated loads by fatigue. Fatigue cracks at welded joints occur because real stress-strain behavior of welded joints is not taken into consideration by standard design. The article is devoted to the stress behavior determination of welded joints in railway girders under external loads and residual stresses. Design deficiencies and technological features of welded girders were identified. These features may increase stresses at welded joints and decrease fatigue life. As a result of studying the existing methods for determining stresses in welded joints, authors used a method, that takes into account the residual welding stresses and design features of welded girder. In this study, the stresses were determined in a cracking area of a girder with the help of finite element modeling. It was shown the correspondence of the stresses in the finite element model and the real girder, tested under the moving load. Retrofitting of stiffeners in welded girders with fatigue cracks was carried out using corner plate connected tightly stiffener and beam flange. Strain measurements under the moving load before and after the retrofitting near cut ribs were taken. The dependence of the stresses at the beam webs was demonstrated near the upper welded ends of stiffeners on the stiffness of rib connections to beam flanges. These findings can be useful at the fatigue life design of the welded elements at building constructions.

Аннотация. Металлические конструкции со сварными узлами подвержены частым отказам при воздействии на них переменных нагрузок. Усталостные трещины в сварных узлах образуются из-за того, что еще на этапе проектирования конструкции не учитывают действительное напряженно-деформированное состояние этих элементов. Статья посвящена определению напряженного состояния сварных узлов железнодорожных пролетных строений от внешних нагрузок. Перечислены технологические и конструктивные особенности сварных пролетных строений, повышающие напряжения в сварных узлах и снижающие их усталостную долговечность. В результате изучения существующих методов определения напряжений в сварных узлах использован метод, учитывающий остаточные сварочные напряжения и конструктивные особенности сварных пролетных строений. Приведены результаты определения напряжений в трещиноопасном узле пролетного строения при помощи конечно-элементного моделирования. Показано соответствие напряжений в конечно-элементной модели и реальном пролетном строении, испытанном под обращающейся нагрузкой. Приведены данные по результатам усиления вертикальных ребер жесткости пролетного строения уголковыми накладками, увеличивающими жесткость крепления ребер к поясу балки. Измерения деформаций стенки балки под обращающейся нагрузкой, выполненные до усиления и после, доказывают на практике наличие зависимости напряжений, возникающих в стенке балки у верхних концов сварных швов прикрепления ребра жесткости, от жесткости прикрепления ребра жесткости к поясу главной балки. Полученные результаты исследований могут быть полезны при проектировании усталостной долговечности сварных элементов строительных конструкций.

1. Introduction

The railway system of Russia comprises more than 11300 metal girders. Half of these girders are welded girders. At such structures, the connections of longitudinal stringers and transverse beams are implemented with high-strength bolts, whereas the connections of stiffeners to the longitudinal stringers and butt joints are accomplished using the machine welding. The bridges in Russia have been employing welding connections instead of riveting ones since the 1970s. However, the short-term operation of welded structures has unveiled their unexpected vulnerability to fatigue cracks forming in weld toes. Nowadays, about 15 % of all welded girders are operated with fatigue cracks.

Fatigue fracture of metals is a result of the action of varied or repeated loads whose value is less than the ultimate static load. Practically, most metal structures fail by fatigue and relatively few by static loads [1]. Fatigue cracks are encountered at mechanical engineering, at aviation, at shipbuilding, and at building structures. It is well known that the fatigue resistance is largely affected by such factors as the magnitude of stresses, the stress cycle asymmetry, the presence of stress concentrators, the residual stresses, and the surface roughness.

In Russia, studies of the fatigue life of welded railway girders were initiated in the 1980s. Large-scale inspections of welded girders were carried out, typical crack formation cases were described, a classification of typical cracks was given, and recommendations on the maintenance and repair of girders with cracks were delivered [2]. By now, it is known more than twenty types of fatigue cracks encountered in metal girders. As a rule, fatigue cracks are located near the welded ends of stiffeners of the main beams or the floor beams. Statistics of welded girders failure shows that the most negative consequences for the strength and for the service life of structures come as a result of the cracking in the beam web (cracks T-9 and T-10) [3]. Such cracks, under development, reduce the load-bearing capacity of longitudinal stringers and transverse beams. Location of such cracks at welded girder is demonstrated at Figure 1.
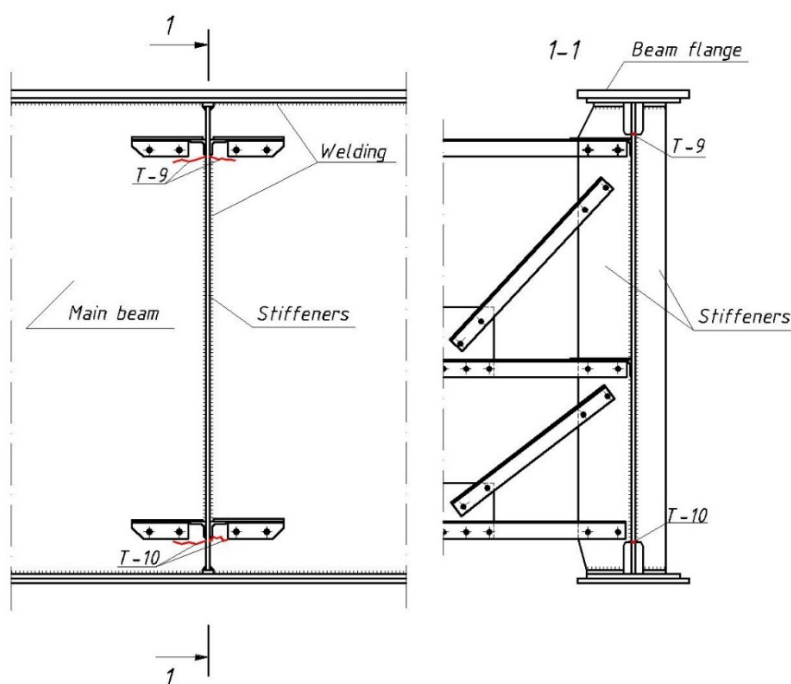

Figure 1. Location of fatigue cracks in welded girders.

In the course of inspections of welded girders, it was found that possible reason for the formation of such fatigue cracks was the loose fit of stiffeners to beam flanges and the off-center action of moving load. As a result, the beam flanges have additional vertical displacements and twisting motions under the load. The beam web experiences bending deformations along stiffener cuts; the latter circumstance led to a substantial growth of stresses at the ends of stiffener welds. An analysis of results gained while performing annual inspections of welded girders shows that, initially, fatigue cracks develop at stiffeners located near supports [2]. It has allowed us to advance a hypothesis about a substantial influence of shear stresses on the fatigue resistance.

In the same years, staff members of several Russian universities have carried out studies on the evaluation of the fatigue life of welded girders. Those studies have shown that, typically, welded joints have a very short fatigue life due to some features of the welding process [4]. A sharp local increase and

decrease of temperature induced by the welding process led to the generation of tensile residual stresses, which, according to research data [5–8], could reach a value of 0.5–0.6 yield strength. Various internal flaws form in the weld due to the violation of the welding process. Such flaws as slug inclusions, weld undercutting, lack of penetration and other flaws act as additional stress concentrators.

The impact of the climatic factor on the crack formation processes in welded girders was analyzed according to the database of the Automated Control System for Artificial Structures (ACS ASs) and the annual inspections data of welded girders. Author has performed the grouping of Russian railways based on climatic-zoning data contained in the Russian Building Rules "Construction Climatology" [9]. All the climatic zones were divided into two groups, those with favorable climatic conditions (average monthly temperature – 0 to -14 °C in January and +12 to +28 °C in July); and those with unfavorable climatic conditions (average monthly temperature below -14 °C in January and 0 to +20 °C in July) [10]. The distribution of welded girders with fatigue cracks of the railway system is shown in Figure 2.
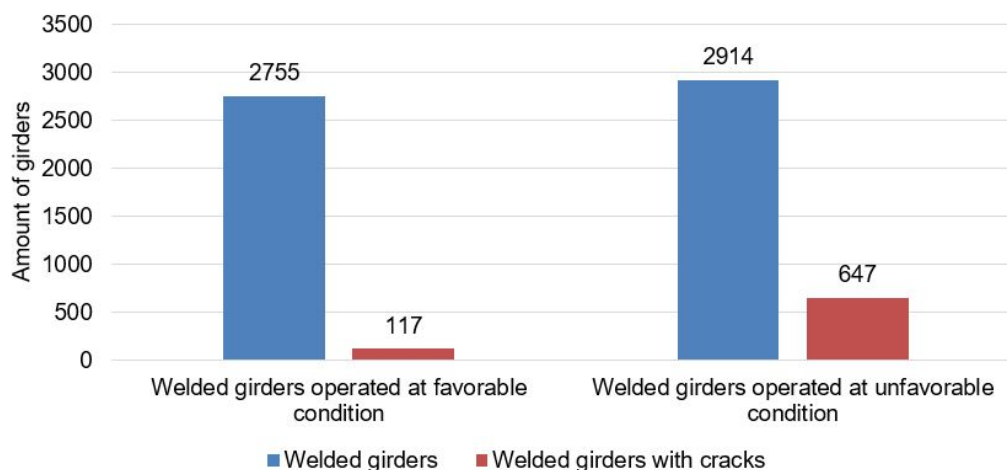

Figure 2. Amount of welded girders with fatigue cracks.

It was established that in the railways with unfavorable climatic conditions the number of welded girders with cracks was six times as much that in the railways with favorable one. Total numbers of welded girders in both groups are equal.

Scientific publications [11–14], engaged in the fatigue life evaluation of welded joints, show that the formation of fatigue cracks in welded beams was a consequence of inaccurate evaluation of the stress-strain behavior near the welded ends of stiffeners. The increase of stresses near the welded ends of stiffeners was a consequence of some specific features of the operation of these structures and the action of the moving loads. Evaluating the stress-strain behavior with all features can be taken into consideration by the finite element method (FEM). It enables to determinate the stress-strain behavior of the structure with allowance for its 3D operation and specific design features.

Different approaches of stress determination were designed using FEM such as nominal stress, hot spot stress and effective notch stress [15]. Nominal stress approach based on huge numbers of laboratory fatigue test results for different weld details with different geometries, a number of design S-N curves that represent a 97.7 % survival probability for the details that are associated with each curve have been provided in the design codes [16, 17].

The hot spot stress approach was originally developed for welded joints of circular and rectangular hollow sections. The structural hot spot stress can be determined using reference points and extrapolation to the weld toe at the hot spot in consideration. The method has been later applied successfully to welded plate structures [18–20]. Evaluation of hot spot structural stress from the finite element analysis was updated by Radaj et al. [21].

The effective notch stress approach is mainly based on the computed highest elastic stress at the critical points, i.e. crack initiation points. This method was proposed by Radaj et al. [22] who took account of stress averaging in the micro-support theory according to the Neuber's rule with a fictitious radius of 1 mm for plate thicknesses of 5 mm and above. For smaller plate thicknesses, Zhang and Richter [23] have proposed the use of a fictitious radius of 0.05 mm, which is based on the relationship between the stress-intensity factor and the notch stress.

However, these researches do not take into consideration welding residual stresses. To accurately analyze crack behavior in fusion welded components Citirik et al. [24] used two finite element softwares (HEAT2D and FRAC2D_WELD). In Li [25] prediction of welding residual stress was performed by using two finite element softwares SYSWELD and FRAC3D. 3D welding simulations were carried out in order to determine the residual stresses which are transported to the 3D fracture analyses.

Also strain-life approach is widely used for fatigue analyses of welded structures. After the strain-life approach was applied the cyclic elastic-plastic strain has to be assessed at the place where damage is expected to develop in the structure. The local strain range is recommended to be determined based on Neuber's heuristic formula [26]. The modified strain criterion-based method for fatigue assessment of structures is discussed in the article [27].

The article [28] shows a method for estimating the reliability of railway girders. A solution describes the probability of failure-free operation at the level of 0.97–0.98. Such solution is relevant for railways of normal traffic conditions with the possibility of providing high-speed rail traffic. This technical method for rapid assessment of the reliability of railway bridges girders can be used as a basis for harmonizing the Russian National Standard and for the further evolution of the codes for high-speed railway.

An analysis of the fatigue studies of welded girders has shown that the formation of fatigue cracks in structural elements in operation is related with a number of factors involving:

– weld residual stresses;

– specific features of the moving loads action and features of the external loads transfer by the bridge deck;

– insufficiently rigid fastening of stiffeners to the flanges;

– bending deformations of beam webs over the stiffener cut length;

– impact of the high range of minimal and maximal temperatures in the region where the girder is operated.

The totality of these factors substantially increases the stresses at cracking area in comparison with design calculations and leads to a shorter fatigue life of welded joints. The most important factor for crack formation is residual stresses after welding, because the welded part is most likely to be identified as the initial location of fracture. Consequently, an accurate and efficient technique for the determination of the weld residual stress distribution is the required starting point for an accurate fracture prediction methodology for welded structures. Fatigue analyses of welded structures should be performed by using FEM.

The purpose of the present study is the determination of the stress-strain behavior of welded joints in railway girders.

In this study the following problems are being solved:

– the determination of the residual stresses value after welding of stiffener by finite element method;

– the evaluation of stresses at the beam web under moving loads;

– the evaluation of the influence of stiffeners' rigid fastening to the flanges over stresses at the beam web.

2. Methods

The finite element model of the metal railway bridge girder was generated in Midas Civil software [29] for determining the girder stress induced by the moving loads action. The model of the girder was approximated with plate elements to model the stiffeners and to take into consideration the bending of the beam webs in two planes. The finite elements were located on the middle surface of the profile [30]. The reinforced concrete slabs of the ballastless bridge deck were also modeled with plate elements. The fastening of plates to the beams was modeled with rigid bonds. Cross bracing was modeled with beam elements. The model view illustration is shown in Figure 3. Moving load was assumed as the heaviest operating electric locomotive with 24.5-tons/axle load. Load displacement on the model of the girder was modeled with nodal forces moving along the model. Application of the moving load in transverse direction is illustrated in Figure 4.
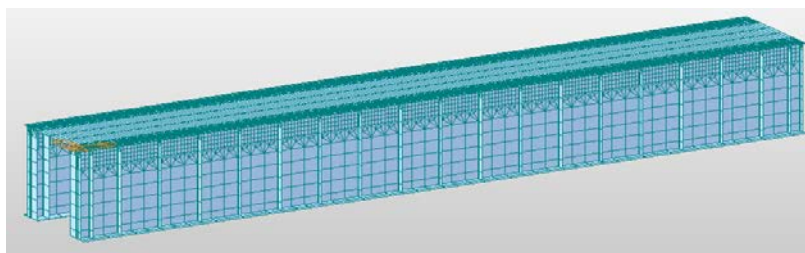
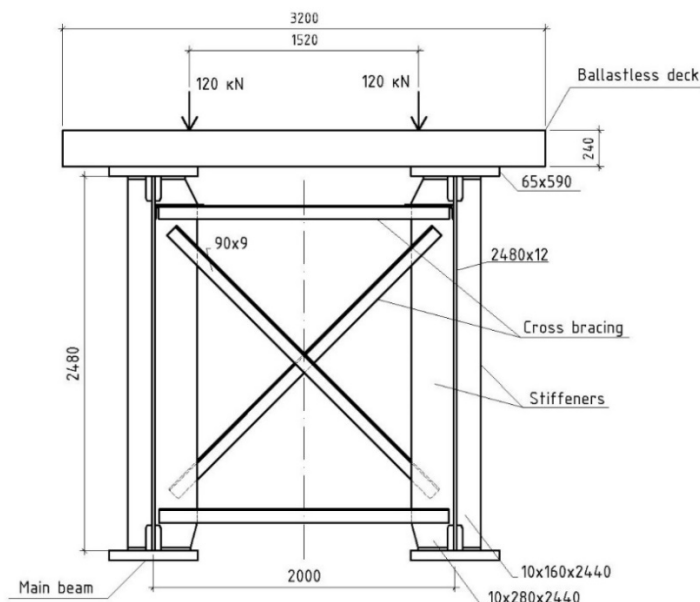**Figure 3. General view of the girder model.**

Figure 4. Application of the moving load.

The welding residual stresses were simulating using Sysweld software [31] for performing thermal calculations. Sysweld solves the problem for the non-stationary statement, thus the software is allowed to take into consideration all thermomechanical phenomena and metallurgical effects. The initial dates for the model are shown in Table 1.

Table 1. The initial dates for the model in Sysweld.

Heat energy, J/mm	Welding speed, mm/sec	Leg of weld, mm	Yield strength, MPa	Young's modulus, MPa	Poisson's ratio
1300	3	7	250	$2 \cdot 10^5$	0.3

Thermomechanical properties were assigned as for low-alloyed steel from the programming library. The solution took into account constitutional change of steel. The Goldak's double ellipsoidal heat source model [32] was used for heat source simulating of arc welding procedures. This model takes into consideration the formation of a recess in the weld pool.

Sysweld evaluated the residual stresses as equivalent stresses defined by the formula:

$$\sigma_{eqv} = \frac{1}{\sqrt{2}} \sqrt{\left(\sigma_1 \sigma_2\right)^2 + \left(\sigma_2 \sigma_3\right)^2 + \left(\sigma_1 \sigma_3\right)^2}, \tag{1}$$

where σ_1, σ_2, σ_3 are respectively the first, the second, and the third principal stresses of the stress behavior, MPa.

The stress-strain behavior of welded joint is determined by using Ansys software [33]. Computed residual stresses from Sysweld were imported into Ansys as pressure. It was possible because the same finite element model was used at Ansys and Sysweld. For this reason, a part of beam model 1 m in length was modeled at Ansys and Sysweld by solid elements SOLID 185. The part of beam model at Ansys was loaded by the computed external forces from Midas Civil and residual stresses from Sysweld. Moreover,

Ansys software is capable to solve contact problems; as a result, software obtains a possibility to model the loose support beam flange on the stiffeners.

The obtained stresses in the finite element model were verified on a real girder under a moving load. The strains in the beam web were measured using the Tensor-MS electronic measuring complex [34]. The complex involves strain gauges and data collector, which are located on the beam web. Also the influence of stiffeners' reinforcement on the stresses at the beam web was studied. The reinforcement was implemented using angel bar connected tightly to the stiffener and the beam flange resulting in fixity of beam flanges. The scheme of reinforcement stiffener is shown in Figure 5. The reinforcement effectiveness was evaluated from the beam web deformations under the moving load before and after the reinforcement. Measurements were conducted under the heaviest operating electric locomotive with 24.5-tons/axle load. The installation of the measuring gauges before and after the reinforcement is shown in Figure 6.
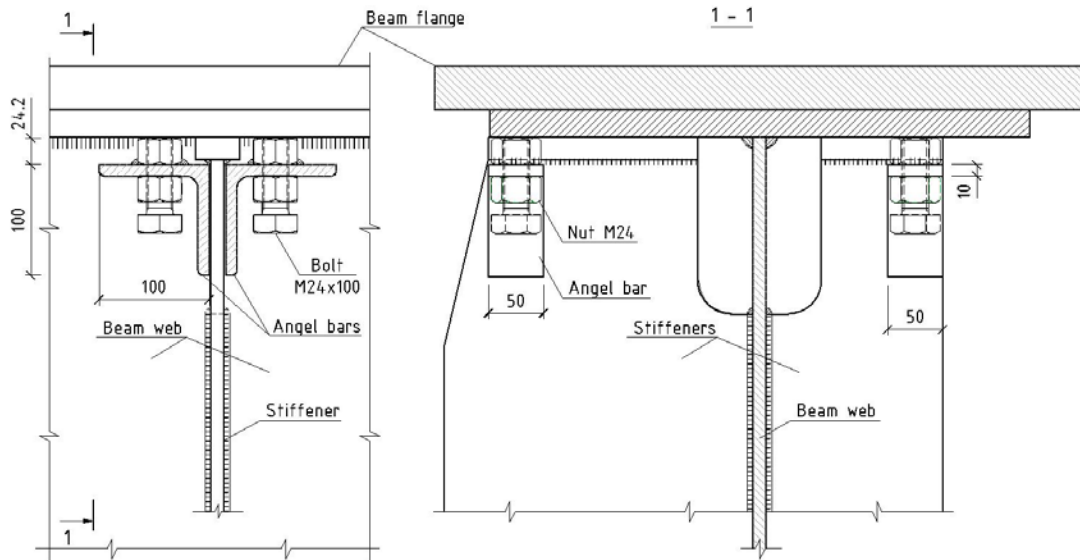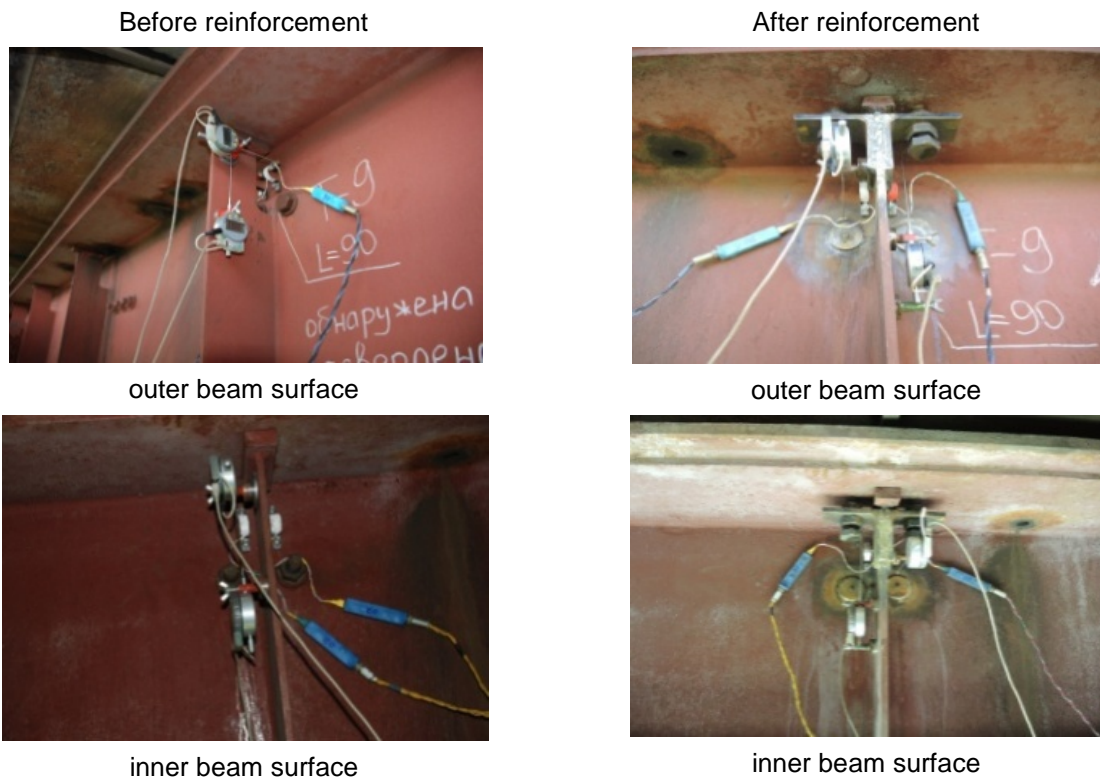
Figure 5. The scheme of reinforcement stiffener.

Before reinforcement · After reinforcement

outer beam surface · outer beam surface

inner beam surface · inner beam surface

Figure 6. Installation of strain gauges.

3. Results and Discussion

3.1. Residual stresses after welding

During the modeling of the welding processes in Sysweld, the temperature reached 1500 °C. A sharp increase of stresses to 120 MPa was observed at the upper and lower edges of weld after cooling to 20 °C. Figure 7 shows the residual stresses after welding simulation.
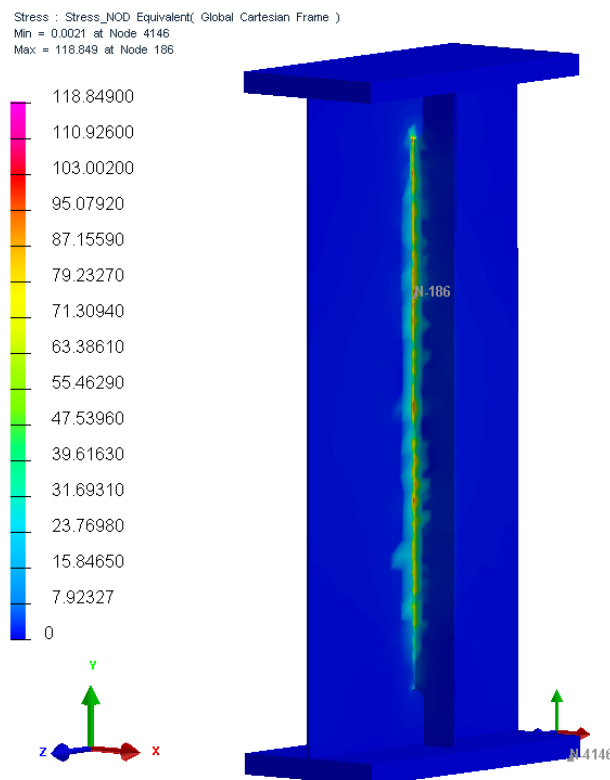

Figure 7. Distribution of residual equivalent stresses after cooling, MPa.

During the experiment residual stress of the weld toe was measured via sin2ψ method by using XRD with Cr-Kα radiation [35]. The surface tensile residual stress approximately corresponded to 100 MPa. Dexter et al. [36, 37] measured residual stresses in welded stiffened panel specimens after fatigue tests. It was demonstrated that these stresses can be idealized by the triangular distribution [36] or the rectangular distribution [37], with peak residual tensile stress equal to the yield strength of the steel under consideration. Tensile regions around the stiffeners are idealized as rectangular or triangular shapes with a base width equal to 10 mm, where the stress level reaches the yield strength of the considered material, σ_o = 235 MPa [38].

3.2. Stresses at the beam web under external loads

As a result of the modeling of the entire girder structure under moving load, it was found that equivalent stresses near the stiffeners reach 15 MPa. The equivalent stresses of the girder model under moving loads in Midas Civil is detailed in Figure 8. In the study [39], finite modelling of truss girder with a length of 55 m under the same load showed that equivalent stresses near the stiffeners reach 30 MPa. However, such stresses are insufficient for the formation of fatigue cracks. Low values of stresses in the model are the reason why the model ignores the residual stresses and the loose support of beam flange on the stiffeners.

Studying the impact of the rigidity of stiffener fixation to beam flanges on the stress behavior near stiffener weld ends, we have modeled four specimens with clearances between the stiffener and the beam flange. Those clearances were equal to 0 mm (no clearance), 0.5 mm, 1 mm and 2 mm. Based on the result, it was plotted the graphs illustrating the variation of equivalent stresses over the beam height. Graphs that illustrate the variation of equivalent stresses over the beam height at near the weld toe on both the outer and inner sides of the beam web are shown in Figures 9 and 10.
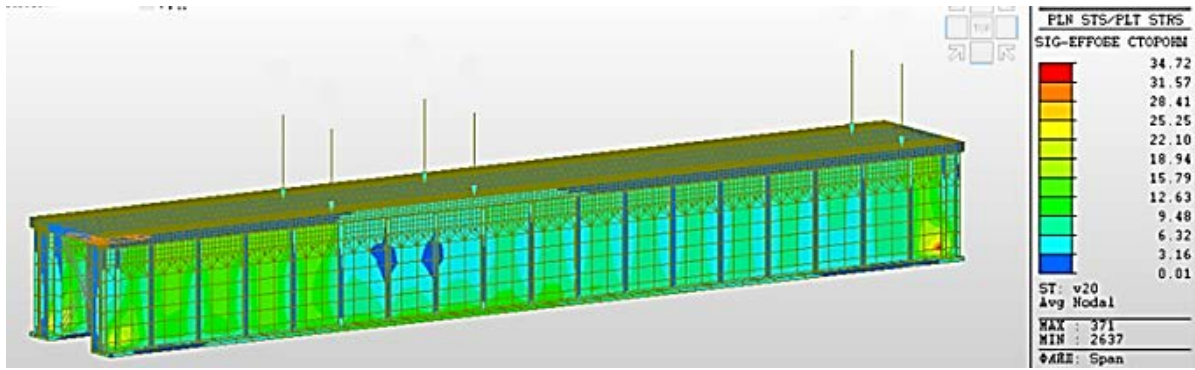
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Figure 8. Equivalent stresses due to the action of the moving loads, MPa.
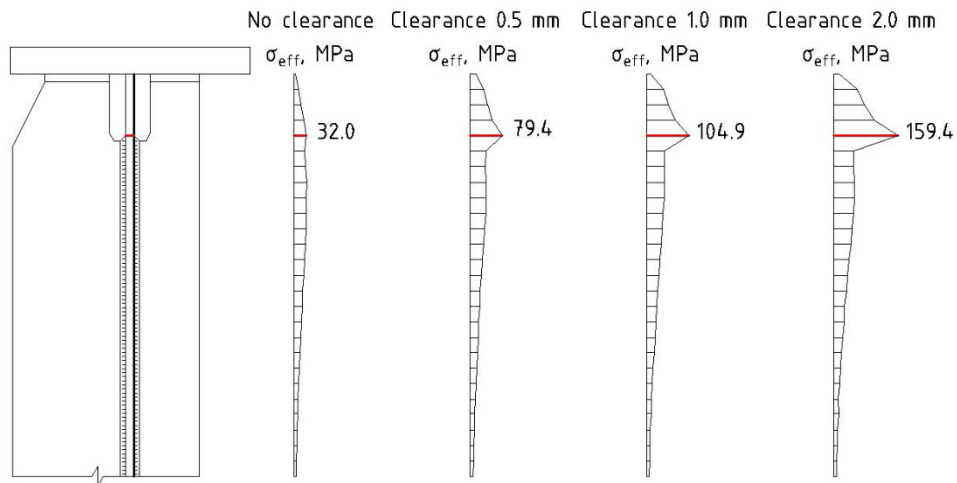

Figure 9. Variation of stresses over the height on the outer surface of the beam web near the weld toe.
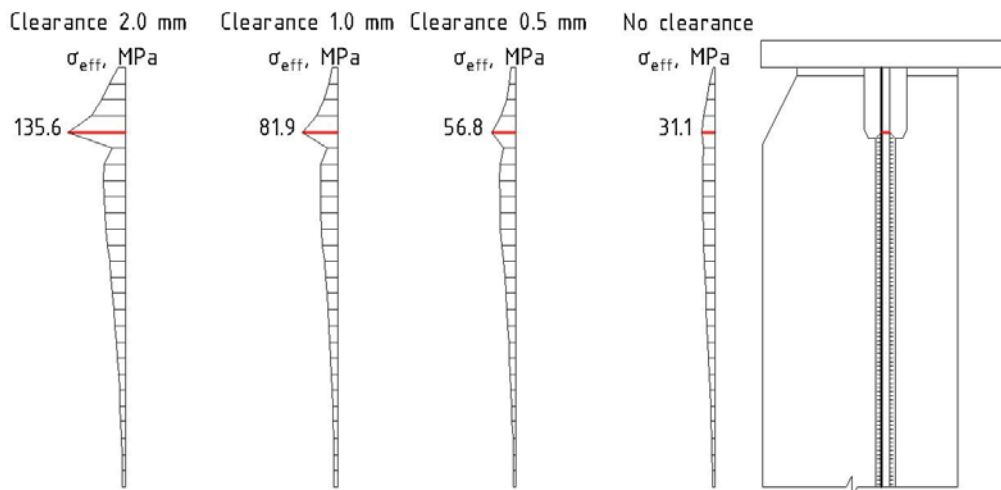

Figure 10. Variation of stresses over the height on the inner surface of the beam web near the weld toe.

The graphs clearly demonstrate the increase of stresses at the weld end and, also, a considerable increase of the stresses in the case of clearance between the stiffener end and the beam flange. In the case of tight fixation of stiffener there are no flexural-torsional deformations of beam web over the stiffener cut length. The latter fact substantially reduces the stresses and prolongs the fatigue life of such joints.

Measurements of strains in the beam web under the moving load showed a good convergence with the finite element model. The effectiveness of the stiffeners reinforcement with angel bar has been demonstrated. The measured stress values are summarized in Table 2.

Table 2. Stresses at the beam web.

	Stresses, MPa	
	inner beam surface	outer beam surface
Before reinforcement	50.0	53.5
After reinforcement	23.4	22.0

The same reinforcement of stiffeners was applied in Seto-Ohashi Bridges in Japan [40]. The stress distributions around the fatigue cracks were measured before and after the repair works by the TSA technique when live loading acted on the bridge and the effectiveness of the severity reduction using these repair methods was investigated [40]. Stresses at connection of stiffener and beam flange under loading were reduced from 186 MPa to 137 MPa after reinforcement. The thermoelastic stress measurement was conducted using an infrared camera with a QVGA InSb array detector [41].

4. Conclusions

1. The numerical simulation has confirmed the influence of service conditions, design and technological features on the fatigue life of welded girders.

2. It was shown that residual stress over the height on the surface of the beam web near the weld toe reach 0.4–0.6 of the yield strength of steel (100–150 MPa).

3. It was shown that stress on the surface of the beam web near the weld toe depends on the rigidity of stiffener fixation to beam flanges. In case of clearance equal to 0.5 mm, stress on the surface of the beam web near the weld toe doubled and reached 60–70 MPa.

4. In practice, the effectiveness of stiffener fixation was proven for reducing the stresses on the surface of the beam web near the weld toe. Rigid fixation of the stiffener led to decrease in stresses near the weld toe in half.

5. It was shown that a combination of several factors increased stresses at the stiffener cuts, and the elimination of one of these factors could decrease the stresses arising due to external load. It should to prolong the fatigue life of the welded joint.

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