CALCULATION OF LOCAL STRESSES IN WELDED JOINT ZONES OF LARGE-SIZED SPACE STRUCTURES

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An approach to calculation of local stresses in zones of welded joints on structures has been developed. The approach is based on introducing absolutely rigid bodies (ARB) in the form of plane sections into the calculation model. According to plane section hypothesis, ARB provides an adequate transfer of external force effects from one fragment model to another, and permits local distribution of stresses in the zones of the welded joints to be investigated, taking into account the 3D work of the entire structure, thus providing a qualitatively new tool to allow for service loading of elements in evaluation of fatigue life.

Keywords: *large-sized space structures, welded joints, local stresses, finite-element method, finite-element model, absolutely rigid body, calculation*

At determination of the level and repeatability of stresses in welded connections it is highly important to take into account the 3D work of the structure. The main method of 3D analysis of the stress-strain state (SSS) of structural connection and elements is the finite-element method (FEM) which allows approximating any deformed body by a model, consisting of a certain type of finite elements (FE). In mathematical terms calculation is reduced to solving a system of equations of equilibrium, consistency of deformations and physical equations.

At calculation evaluation of welded connection SSS it is necessary to adequately reflect the nature of element interaction in structural stress raiser zones with welded joint geometry. Therefore, it is necessary to approximate the entire structure by 3D FE. It is extremely difficult to perform calculations with such a detailed approximation of all the components and elements. Such calculations require application of high-power computers and are performed in exceptional cases. In common engineering practice calculation of local stresses in welded connections of metal structures of industrial buildings and engineering constructions is related to their separation into individual fragments and stage-by-stage analysis of SSS [1]. The welded structure is first considered as a rod model with specified loads and fastening conditions. Then a fragment with the studied welded connection is separated from the rod model of the entire structure and it is represented as shell FE. After calculation of a fragment from shell FE, the welded connection is separated from it, and is represented by 3D FE. Calculation of the latter gives volume distribution of SSS of each structural element present in it. In such cases, basic and quite difficult to implement is the need to establish at transition from one calculation model of a fragment to another one (with a more complex approximation), the boundary conditions in the form of nodal ties and external force impacts derived in calculation of previous fragment SSS. The complexity is increased in the case of structure operation under alternating loading, leading to a change of the nature of interaction of structural elements of welded connections. In order to adequately represent the influence of external alternating impacts on SSS in the analyzed points of welded connection at different loading schematics, it is necessary to develop new boundary conditions for each calculation model of a fragment. This makes it more difficult to perform structure design, and analysis of the level and nature of stress variation in individual elements of welded connection at the same initial conditions (specifying the design characteristics, design loads and their comparison criteria).

At the same time, in calculations of building structures, in particular, concrete, such an FE as an absolutely rigid body (ARB) is used, which allows creating a rigid constraint between models of fragments, consisting of various FE types [2, 3]. It is used for transfer of information on SSS from one part of structure model to another one. Used as ARB is one of the structural (connecting) elements, as a result of which the entire structure is considered as one calculation model. The idea of ARB application in the form of structural elements is quite good and well-proven at rather simple forms of transition: combining the model of a column of industrial buildings with the model of covering plate from plate FE; combining rod models of ribs of bridge structure beams with the roadway slab from plate FE, etc. At evaluation of welded connection SSS, however, it is difficult to apply ARB in the form of a structural element, as the transition itself (welded connection) should be analyzed.

As deformation of welded structure stressed elements quite satisfactorily obeys the plane-section hypothesis, at each transition from one calculation model of a fragment to another one, it is the most rational to introduce ARB not in the form of a structural element, but as plane ARB — section of structural element of the next model. If certain conditions of interaction of ARB in the form of a plane section with fragment models are followed, it is believed to be possible to perform, using FEM, calculations of local stresses in welded connections of structures of any degree of complexity, adequately transferring hereditary information about SSS from one calculation model to another one, allowing for the loading fea-

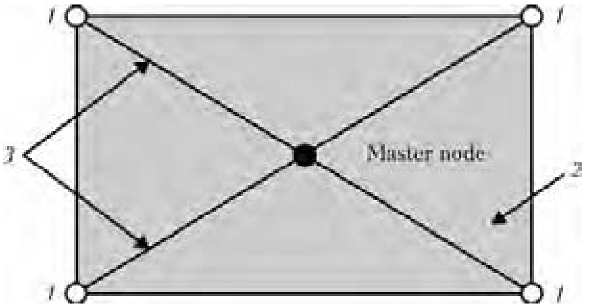

Figure 1. ARB schematic: *1* — master node; *2* — ARB; *3* — rigid connection between the nodes (radius-vector)

tures. When ARB in the form of a plane section is used in interconnection with plane-section hypothesis, it is important to ensure fulfillment of the two main conditions: master nodes of the previous model and slave nodes of the next model are located in one plane; interaction of master node with the slave one is taken to be such, at which the regularity of structural element behaviour is preserved. Here, displacements u_s and angles of rotation θ_s of each slave node are connected through radius-vector ρ_{m-s} (Figure 1) with displacements u_m and angles of rotation θ_m of master node by the following dependence:

$$\begin{pmatrix} u_s \\ \theta_s \end{pmatrix} = \begin{pmatrix} u_m + \theta_m \rho_{m-s} \\ \theta_m \end{pmatrix}.$$

In this work a procedure is proposed for calculation of local stresses in the zones of welded joints of large-sized space structures using ARB. In terms of the proposed procedure such notions as structure fragment and node are introduced. A fragment is any part of the structure, including a node. Taken as the node is that part of the structure (fragment), in which the mutual influence of structural elements on its SSS is manifested. For analysis of the real work of the studied welded connection, using standard FE library, one 3D FE model of the entire structure is created with the specified accuracy of approximation of the accepted structural forms. This model, allowing for space interaction of structural elements, analyzes welded connection SSS based on successive consideration of models with different types of FE (Figure 2, *A*–*C*): rod model of a structure, shell model of a fragment, and 3D model of a node.

At the first stage the rod model is considered, in which the structure load-carrying elements are approximated by rod FE with the respective rigidity

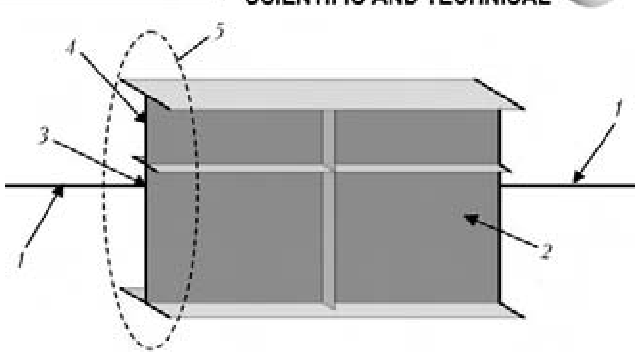

Figure 3. Schematic of introducing ARB between the rod and shell models: *1* — rod FE; *2* — shell model of structure fragment; *3* — center of gravity of section; *4* — ARB; *5* — section of structural element of shell model of fragment

characteristics. Forces in all the elements are determined by the results of its calculation. At the second stage rod FE in the analyzed locations of the structure are replaced by 3D model of the fragment.

For adequate transfer of membrane and bending forces through ARB from rod model *A* to shell model of fragment *B* (see Figure 2), master node is introduced by rod FE and is located in the center of gravity of the section of adjacent structural element of a fragment with shell approximation, and slave nodes are represented by shell FE (Figure 3).

At the third stage in the locations of analyzed welded connection *C* (see Figure 2) shell FE are replaced by connection model with 3D FE approximation (Figure 4, *a*). Here transfer of membrane and bending forces through ARB from shell model of fragment *B* to 3D model of welded connection *C* (see Figure 2) is ensured as a result of superposition of median surface of shell FE on the neutral line of 3D model section. Master nodes are assigned by shell FE, and slave nodes — by 3D FE. Master and slave nodes belong to FE face of the next model (Figure 4, *b*).

So, the constructed calculation model of a structure with ARB ensures adequate transfer of external force impacts from fragment to fragment and enables studying local stress distribution in welded joint zone, taking into account 3D work of the structure. Its application greatly simplifies analysis of the actual operation of structure welded connections, allowing for interaction of structural elements included into the connection at application of alternating load, for instance, reversed load. Thus, the procedure provides a qualitatively new tool for analysis and allowing for

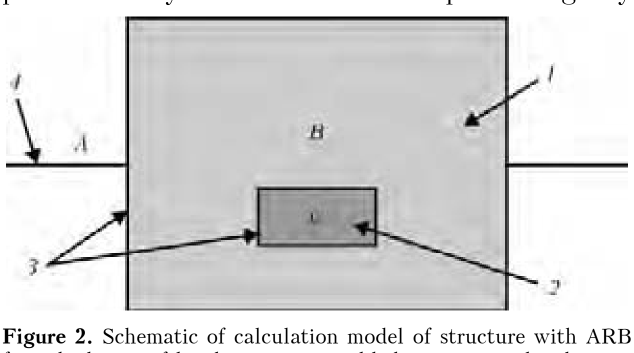

Figure 2. Schematic of calculation model of structure with ARB for calculation of local stresses in welded connections by the proposed procedure: *1* — shell model of structure fragment; *2* — 3D model of welded connection; *3* — ARB; *4* — rod model of structure

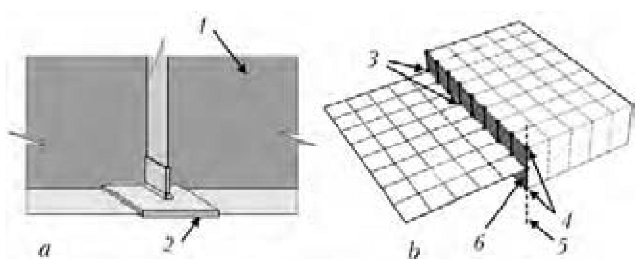

Figure 4. Replacement of shell FE by 3D model (*a*) and introduction of ARB between the shell and 3D FE (*b*): *1* — shell model of structure fragment; *2* — 3D model of connection; *3* — master nodes; *4* — slave nodes; *5* — face with master and slave node; *6* — ARB

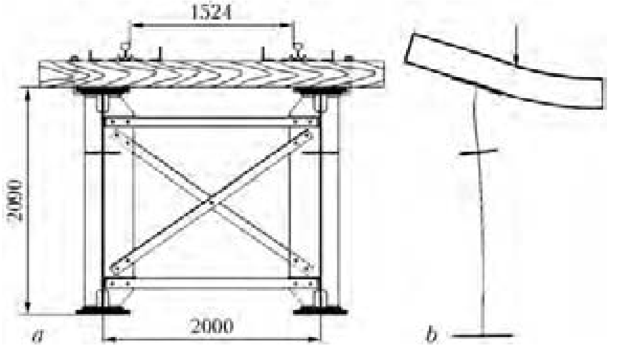

Figure 5. Cross-section of welded span structure of bridge (*a*) and out-of-plane deformation of its web (*b*)

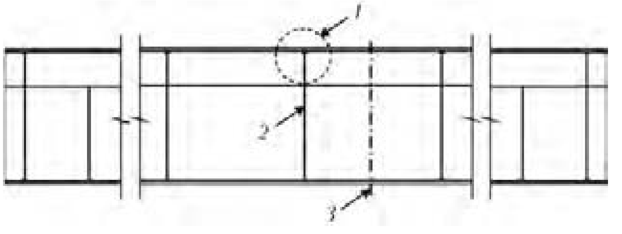

Figure 6. Location of the analyzed welded connection: *1* — analyzed welded connection; *2* — transverse stiffener; *3* — span middle

service load of welded connections at assessment of fatigue life of structures operating under the conditions of alternating impacts.

In operation of bridge span structures the most critical elements are welded connections, exposed to

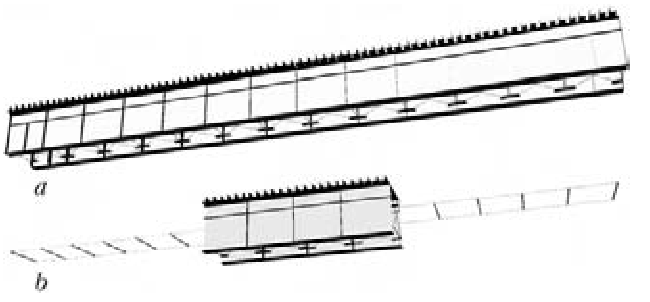

Figure 7. Calculated models of all-welded span structure (for explanations see the text)

direct impact of vehicles [4]. Their fatigue strength largely depends on the features of element interaction, allowing for application of concentrated loads. Therefore, for substantiation and evaluation of the proposed procedure effectiveness, calculation of SSS of a welded connection of a typical all-welded span structure of a railway bridge was performed.

The span structure consists of two welded girders with 27 m span, combined into space structure by a system of longitudinal and transverse braces (Figure 5, *a*). Height of girders is equal to 2.09 m, distance between their axes is 2 m. Girder webs are strengthened by transverse stiffeners with 2 m spacing, as well as longitudinal stiffeners along the entire span length. Bridge deck is supported by wooden sleepers.

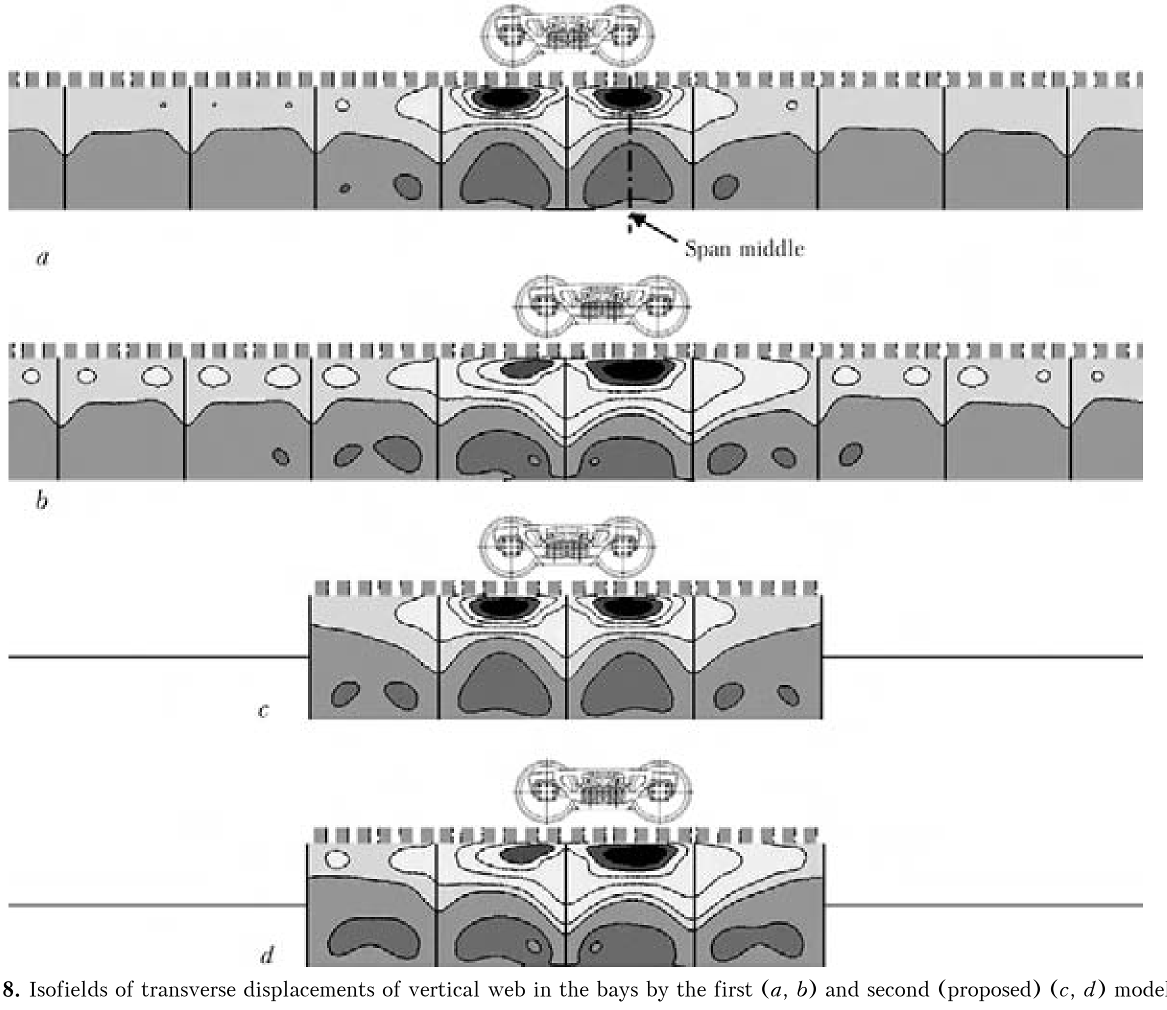

Figure 8. Isofields of transverse displacements of vertical web in the bays by the first (*a*, *b*) and second (proposed) (*c*, *d*) model

Passage of each axle of moving load has an important influence on formation of span structure SSS that, in its turn, causes a change of local interaction of elements. In addition to the main bending of the girders, it also leads to torsion of the upper girth and out-of-plane deformation of its web in the bays (Figure 5, *b*), as well as local bending of elements in the zone of transverse stiffeners. Local interaction of elements changes significantly, depending on the moving load position. Therefore, fatigue analysis of welded connections should take into account the features of the nature of change, quantity and repeatability of the applied alternating impacts.

As verification calculation for substantiation of the proposed procedure postulates, SSS of elements of a welded connection for welding transverse stiffeners in the span middle part (Figure 6) obtained from two calculation models was compared, taking into account the different position of the freight car truck. The first model approximated the structure load-carrying elements by shell FE along the entire length of the span (Figure 7, *a*), and the second model was constructed by the proposed procedure (Figure 7, *b*).

At analysis of formation of span structure SSS by the results of numerical calculation by the first model a marked dependence of the nature of structure element interaction on moving load position was noted. Truck axle passage over the adjacent bays essentially influences the redistribution of web SSS. At symmetrical position of the truck relative to the transverse stiffener, a symmetrical deformation of the web develops in the bays adjacent to the analyzed welded connection (Figure 8, *a*). Maximum transverse deformations of one sign form in the web upper parts, and those of the other sign form in the lower part. This corresponds to S-shape of transverse out-of-plane bending of the web. Here, welded connection elements have their own quite definite kind of loading. As truck axle approaches the transverse stiffener, SSS redistribution starts, leading to asymmetry of web deformation (Figure 8, *b*). Loading level of connection elements is changed. By the results of investigations of the regularities of web SSS change in the adjacent bays at load passage, it is established that in order to represent an adequate loading of welded connection, it is necessary to analyze a fragment, including four bays.

Comparison of the results of calculation by the first and second models (see Figure 8) showed that regularities of SSS formation in the considered sections practically coincide by their nature and level. SSS can slightly differ on fragment boundaries. On the other hand, it does not in any way affect the results of analysis of the studied connection. Thus, in order to determine the real work of welded connections of span structures, it is quite sufficient to perform detailed approximation of just the fragment, in which the analyzed welded connection is located.

Equivalence of evaluation of web SSS in the studied bays by both the models, allowed performing comparative analysis of SSS formation in the zone of interruption of a weld made for attachment of the transverse stiffener to the web. By the results of calculations it was established that the 3D model has an adequate loading through ARB in the form of a plane section, that is indicated by the similarity of displacements (Figure 9, *a*, *b*). On the other hand, the nature of distribution of local stresses in the models differs significantly. Local stresses in the weld zone in the 3D model give a more comprehensive representation of its actual condition (Figure 9, *d*). Therefore, in evaluation of service life of span structures analysis of the nature of the change in local SSS of welded connection by 3D model is preferable.

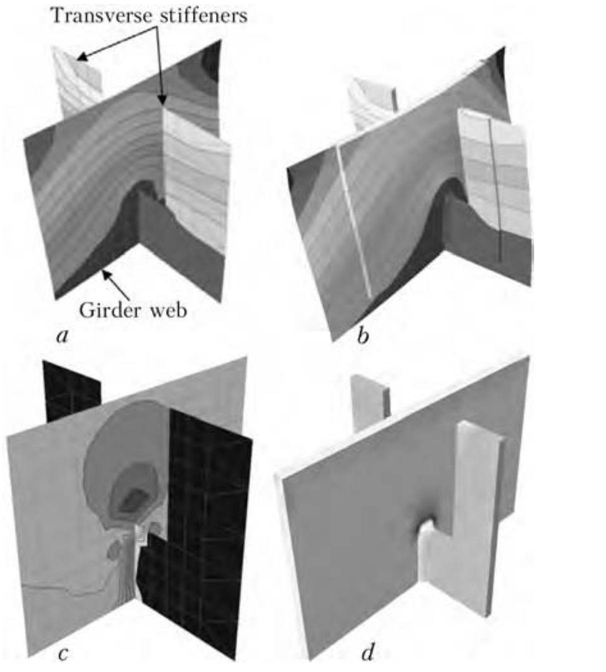

Figure 9. SSS in the zone of interruption of weld made for attachment of transverse stiffener to the web of span structure: *a*, *b* — isofields of transverse displacements of elements in the shell and 3D models; *c*, *d* — distribution of local stresses on the outer surface of the girder web in the shell and 3D models, respectively

Thus, introduction of ARB in the form of a plane section connecting in one calculation model of the structure fragments from FE of different types, greatly simplifies analysis of the real work of welded connections, allowing for 3D interaction of structural elements included into the connection under the conditions of alternating loading. ARB in interrelation with the plane-section hypothesis ensures an adequate transfer of external force impacts from one model of the fragment to another one and enables studying the local distribution of stresses in the welded joint zone, allowing for 3D work of the entire structure. This provides a qualitatively new tool for allowing for service loading of elements in evaluation of fatigue life of various-purpose metal structures.

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