Modeling and testing of three-point bending of rectangular hollow sections for vehicles and highway guardrails

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Abstract. Steel hollow sections are common for transport engineering, vehicles, highway guardrails. The special requirements for strength and stiffness are determined by tests. The three-point bending test experimental and FEM research were carried out on steel rectangular hollow sections (RHS) with a cross section of 40 mm × 50 mm, manufactured in two ways: (a) by cold bending of steel strips on roll-forming mill in semi-closed section with a longitudinal gap of 0.5 mm between the edges formed on a 40 mm web (B-RHS); (b) similar cold roll-forming to the closed section and welding with a longitudinal weld along the web middle of 50 mm (BW-RHS). As a result, the graphs and analytical equations for relating the force (P) and deflection (J) at load on 50 mm and 40 mm webs were obtained, and revealed the advantages of bent-welded sections (BW-RHS) by stiffness and strength. FEM was performed using the SolidWorks CAD/CAE system for various RHS wall thicknesses (t = 1.93 mm, 1.84 mm and 0.7 mm). It is shown that the BW-RHS design increase the stiffness by at least 50%, reduce the wall thickness by 61.9% while maintaining the same stiffness and ensuring the high strength indices for the case of least loading on the larger web, i.e. the maximum stresses in the RHS webs will be 2.33 times less than the yield stress of low-carbon steel.

1. Introduction

Rectangular hollow sections (RHS) are of great importance for many industries, such as shipbuilding, mechanical engineering, construction, construction of framework and reinforced concrete structures, etc. [1, 2]. In automobiles, hollow sections are located in thresholds, body and window elements, energy-absorbing members [3], as well using as highway guardrails, pedestrian safety fences, etc. Due to the prevalence and increasing demand for hollow section, the requirements for the geometric parameters and strength of such products are becoming more stringent, for that standards have been developed in the European Union [4–6] and most developed countries of the world [1, 5]. For the manufacture of hollow sections with required service properties different fabrication methods are used [1, 7–12]: skew roll piercing process, pilger process, Fretz-Moon pipe process, induction welding process, spirally bent strip welding, and rectangular hollow section roll-formed from circular hollow section. The processes of sequential bending of the section on multi-roll roll-forming mills to closed section with longitudinally welding of edges at finishing have proved to be satisfactory [1, 8, 12]. The improvement of designs, production and quality control of these products is constantly given considerable attention. Therefore, the development of methods of experimental research and modeling.
of the section behavior of various structures remains extremely relevant [5–8, 13, 14], which allows to identify the advantages and disadvantages of new solutions in manufacturing of RHS.

Research on stiffness of sections is conducted by bending test. The experiments are carried out according to standardized methods by loading sections by four-point or three-point scheme [5, 13]. It is quite common to combine experimental tests with computer simulation of the test process [5, 14, 15]. The latter requires an account of the physical conditions of the test deformation, the complexity of the geometric shapes of the section and the material properties of the specimens to be as accurate as possible, which presents certain difficulties [5–7, 13–16]. Studies of the complex characteristics of strength and stiffness are performed for sections of different shapes (open and closed) [17], of different materials (including non-metal) [18–20], non-welded and welded [2, 14, 18, 21, 22], taking into account the complexity of the shape of the final product, location and load in real construction [17, 21, 22]. This defines the deflection values as the characteristics of sections stiffness, and magnitudes of stresses as characteristics of sections strength. Certain progress has been made in testing and modeling the section loading process by three-point bending, when the section is viewed as a beam supported on round supports and deformed along the axis of symmetry by a rounded die. As a result, the behavior of the walls and webs of the section, different buckling shapes [4, 13, 17], revealed critical values of forces and stresses have been described. The main result of the tests on the stiffness of the sections is to obtain a graphical dependence of the deflection values on the load force [13–16]. In some cases, instead of the deflection values, they determine the parameters of the beam curvature [6] at loading or analytically calculate the bending angle between the bent beam and the horizontal axis [23]. It is particularly difficult to consider the multilayer sections when using coated specimens [16, 19, 24, 25]. When testing galvanized sections, the thickness of the zinc coating is generally neglected. Changing the design of RHS or introducing bending technology with longitudinal welding of closed section edges requires evaluation of the indices of stiffness (deflection) and strength (stress) of metal products to identify the advantages or disadvantages of new production processes.

The results of the behavior study of the same type sections with different variants of manufacture, after the tests will allow to establish dependencies between the forces and deflections, to estimate the difference of deflections at the same values of loads, and to compare the magnitudes of stresses in the section webs, which is a scientific originality of work. The practical value of the study is to identify the reserves for reducing the material consumption of BW-RHS.

2. Purpose of the Work
The purpose of the work is to determine the differences in the complex operational characteristics of stiffness and strength of the steel hollow section with a cross section of 40 mm x 50 mm, made of multi-roll forming of the steel beam on a roll-forming mill into a semi-closed section with a gap between the edges not more than 0.5 mm, formed along a web with a size of 40 mm, and a section made of multi-roll forming of the beam from galvanized steel on a roll-forming mill in a closed section and subsequent welding of the edges with the longitudinal weld on the middle web with a size of 50 mm. Comparing these types of sections with the gap and the presence of the weld will allow to see differences in the behavior of products of similar cross-section and different variants of manufacture with differences in thickness, and, as a consequence, to evaluate the prospects of reducing the material consumption of the BW-RHS while ensuring equivalent stiffness values.

3. Material of Research
For the experimental study, the sections of different manufacture (Fig. 1) were pre-examined and prepared for testing. The sections did not have any visible defects. From each type of section three specimens of profile with a length of 1000 mm were cut out. The electronic caliper “Digital caliper A46”, which was metrologically verified within the specified time, was used to measure the thickness. 10 measurements of the wall thickness of the workpiece for each type of section were performed and statistical data processing was performed. Statistical verification of the adequacy of these experiments’ description was performed according to the F-test, and the verification of experiment reproducibility
was performed according to Cochran’s test. It was established that the B-RHS with a cross section of 50 mm × 40 mm have an average wall thickness of 1.936 mm, and the BW-RHS with a cross section of 50 mm × 40 mm have an average wall thickness of 1.843 mm.

The main determining parameter characterizing the stiffness of the section is its deflection on three-point bending. The method of three-point bending was chosen for testing (Fig. 2). According to the principle indicated in Fig. 2, a test methodology using the experimental installation shown in Fig. 3 was developed. To load the section by three-point bending through a cylindrical spacer with a diameter of 5.9 mm, a tensile machine UMM-10 with a maximum load of 100 kN was used. The deflection of the section was recorded with a mechanical dial gauge from the exemplary portable dynamometer DOSM-33 (Fig. 4). To detect these indicators of force \( P \), a scale built in the UMM-10 was used, the change of indices throughout the experiment was recorded by a set camera in continuous recording mode (see Fig. 3).

\[
\begin{align*}
\text{Figure 1.} & \quad \text{B-RHS (a) and BW-RHS (b) cross sections 50 mm} \times \text{40 mm.} \\
\text{Figure 2.} & \quad \text{Scheme of RHS bending by three-point bending.} \\
\text{Figure 3.} & \quad \text{Installation for experimental study.} \\
\text{Figure 4.} & \quad \text{Exemplary portable dynamometer DOSM-33 (left) and section deflection indices \( f \) (right).}
\end{align*}
\]

The same scheme was used to monitor the deflection of section \( f \), capturing the gauge data using a second high-resolution camera. 50 mm web load (force \( P(50) \)) and 40 mm web load (force \( P(40) \)) were applied. Three fully recorded trials were conducted for each section type and cross section. The “DaVinci Resolve 15” software (to synchronize the operation of both cameras) and the Microsoft Excel options were used to process the results of the force and deflection experiment during three-point bending. The data obtained from the video made it possible to compare the synchronized changes in the force \( P \) and the deflection of the section \( f \) over time, that were used to build the graphical dependencies shown in Fig. 5 and Fig. 6.

After processing the obtained graphical dependences of the deflection on the load force, regression equations were obtained. It was established that the functional dependence of the deflection on the load value is most accurately described by the power equations with the coefficient of determination \( R^2 > 0.95 \):

- for B-RHS:

\[
\begin{align*}
\text{(1)} \quad f &= 0.0644 \cdot P(50)^{0.6452} \\
\text{(2)} \quad f &= 0.0249 \cdot P(40)^{0.6524}
\end{align*}
\]
The study of the stress-strain state of sections was performed on a solid-state deformable model using the CAD/CAE systems of SolidWorks. The geometric parameters of the model are fully consistent with the full-scale specimen and are made in a scale of 1:1 (geometric similarity). As the external load applying to the specimen is transmitted through a cylindrical spacer, a similar element was additionally taken into account in the model. The study was performed under options of loading by three-point bending on different RHS webs. For each option, diagrams of equivalent stresses in the model and linear deflections in the model were determined. The calculated loads and their combinations are taken in accordance with the experiment carried out on full-scale specimens.

- for BW-RHS:

\[
 f = 0.0151 \cdot P(50)^{0.7465} \\
 f = 0.0275 \cdot P(40)^{0.6385}
\]

The specimens under study: specimen 1 – BW-RHS with cross section 40 mm × 50 mm and thickness of the wall \( t = 1.86 \text{ mm} \); specimen 2 – B-RHS with cross section 40 mm × 50 mm and thickness of the wall \( t = 1.93 \text{ mm} \); specimen 3 – RHS with cross section 40 mm × 50 mm and thickness of the wall \( t = 0.7 \text{ mm} \) (validation of results). Plain carbon steel was selected from the standard material library as model material.
In order to find solutions for reducing the RHS material consumption, it is important to have a general picture of the stress-strain state. Obtaining this data is possible by creating a calculated three-dimensional model. To determine the actual stress-strain state, FEM was used, which was implemented in the CAD/CAE system environment.

By “Simulation” means, a finite element grid was created. For the computational models, the joint restraint of supports was used. This type of fixing made it possible to model the process of rotation of the specimen relative to the metal beam (support) as a result of deformations. When calculating these models, the specimen's own weight was not taken into account. The simulation results are given in Fig. 7 – Fig. 12.

![Figure 7](image1.png)
Figure 7. Diagrams of stresses and their values in the lower web according to the first option of loading of specimen 1.

![Figure 8](image2.png)
Figure 8. Diagram of deflections according to the first option of loading of specimen 1.

![Figure 9](image3.png)
Figure 9. Diagrams of stresses and their values in the lower web according to the first option of loading of specimen 2.

![Figure 10](image4.png)
Figure 10. Diagram of deflections according to the first option of loading of specimen 2.

![Figure 11](image5.png)
Figure 11. Diagrams of stresses and their values in the lower web according to the first option of loading of specimen 3.

![Figure 12](image6.png)
Figure 12. Diagram of deflections according to the first option of loading of specimen 3.

The following was established, as a result of the analysis results of stress-strain state modeling:
(i). Specimen 1 (BW-RHS, $t = 1.86 \text{ mm}$) at identical loading and in equivalent sections with specimen 2 (B-RHS, $t = 1.93 \text{ mm}$) has higher strength. Maximum values of equivalent stresses for specimen 1 (BW-RHS) were $23 \text{ MPa}$, and for specimen 2 (B-RHS) − $30 \text{ MPa}$ correspondingly;

(ii). Specimen 1 at identical loading schemes and in equivalent sections with specimen 2 has higher stiffness. Maximum deflection for specimen 1 were $f = 0.46 \text{ mm}$, and for specimen $2 - f = 1.55 \text{ mm}$;

(iii). Specimen 3 (BW-RHS, $t = 0.7 \text{ mm}$) at identical loading and in equivalent sections with specimen 2 (B-RHS, $t = 1.93 \text{ mm}$) has less strength, since maximum equivalent stresses were $77 \text{ MPa}$, and for specimen $2 - 30 \text{ MPa}$. In this case, the resulting stresses are much smaller than the yield stress of a given carbon steel ($\sigma_y = 175…195 \text{ MPa}$);

(iii). Specimen 3 at identical loading and in equivalent sections with specimen 2 has similar stiffness, i.e. maximum deflection were $f = 1.54 \text{ mm}$, and for specimen $2 - f = 1.55 \text{ mm}$.

4. Conclusions

Standard methodology for experimental studies of B-RHS on three-point bending by applied force with continuous video recording of test process to obtain the dependence between the load value and the deflection of the section was improved. The graphical and analytical dependences of the deflection of the section under the options of loading on a larger web and on a smaller web from the load magnitude were obtained. The analysis of graphical dependencies revealed that despite $4.8\%$ smaller thickness of BW-RHS in comparison with B-RHS, the deflection for the most unfavorable load case (on the larger web) is reduced by $59\%$, and on the load on the smaller web the deflection is reduced by $0.7\%$. Thus, the presence of the weld increases the stiffness and strength of the RHS. BW-RHS will allow to achieve the required parameters of the section stiffness while reducing the thickness of the initial strip, i.e. by saving of workpiece metal. It was established that the manufacture of BW-RHS has advantages in terms of stiffness over B-RHS. For the most unfavorable option of loading the section to the larger web, when the non-welded gap is on lateral web, the option of forming a weld will give an improvement in the stiffness of at least $50\%$.

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