Structural factors influence on strength properties of S235JR steel welded joints

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Abstract. The paper presents the results of strength tests of welded joints of S235JR structural steel. Welded joints of various geometries were made: butt joints, overlap joints with a single weld, overlap joints with double welds, overlap joints with spot welds, overlap joints with hole welds, and double-flanged seam. The strength tests carried out made it possible to determine the destructive force. Eight joints of each type were made. Based on the results obtained, a statistical analysis was carried out to determine the influence of structural factors on the strength of welded joints and to assess the repeatability of the process of making joints of a given type. This analysis allows verifying which of the tested geometries of welded joints are the most strength and stability, which is especially important when designing new structures or planning renovation of existing structures. The analysis showed that the highest strength as well as the highest repeatability was obtained in the case of overlapped joints with double welds – destructive force at 37,367 MPa. The lowest strength was characterised by double-flanged seam – destructive force 8,603 MPa.

1. Introduction
Bonding is a technological operation that provides inter-atomic bonds that guarantee the continuity of the crystal chain in the joining area. Due to the method of obtaining a connection, the following modern bonding methods can be distinguished: welding, pressure welding, soldering, brazing, resistance welding, solid-state welding, and adhesive bonding [1–6] which successfully replace the riveting [7, 8]. Coherent joints are used in various technical fields, as described in several publications [9–16]. These types of joints enable to combine dissimilar materials [17–19]. Welding technologies enable additive manufacturing [20, 21] or coatings deposition [22, 23], thus allows to obtain structures that could not be created using basic production technologies, such as casting or plastic forming. In this work, one of the above-mentioned methods was used, which is MMA welding (Manual Metal Arc Welding).

The basic prerequisite for the correct welding process is the stability of the welding process. Monitoring of the welding arc stability is commonly performed by measuring and recording and analysing the following parameters: welding current and arc voltage, and additionally: shielding gas flow rate, welding speed, and wire feeding speed [24, 25].

The practical application of such an extensive field of knowledge as welding is conditioned, apart from the issues related to the welding of materials, by the use of various welding equipment [26–28]. Currently, welding is widely used [4, 5, 28], first of all in the construction of lifting machines and equipment [29, 30], and also in the construction of structures such as bridges, pipelines, tanks [31–35].
The most commonly used criterion for assessing the quality of welded joints is the strength of the weld. The main factors influencing the quality of a joint are the welding method, the amount and concentration of energy supplied, the materials to be joined, the material of the electrode or flux, as well as the geometry and design of the joint. When checking the quality of welds using destructive and non-destructive methods, the following factors are also considered: defects in the weld, the acceptable level of distortion, the properties of all joint zones [24].

Because of the wide range of applications of welded joints, joint geometries can be different, so research has been undertaken to assess the influence of structural factors such as joint geometry on the strength of welded joints of S235JR steels. The quality of the joints was evaluated based on the results of the destructive test.

2. Research methodology

2.1. Characteristics of materials
The test samples were cut from a 3 mm thick sheet of S235JR structural steel. This is non-alloy steel with good weldability. The mechanical and physical properties and chemical composition of the sheets used are presented in Tables 1 and 2.

| Table 1. Mechanical, physical properties of steel S235JR according to EN10025-2:2005 [36]. |
|-----------------------------------------------|-------------------|------------------|
| Tensile strength, Rm | Yield strength, Re | Elongation, A |
| 360 - 510 MPa | ≥ 235 MPa | >26 % |

| Table 2. Chemical composition of steel S235JR according to EN 10025-2:2005 [36]. |
|-----------------------------------------------|-------------------|------------------|
| Steel grade | Chemical composition [%] |
| S235JR | C | Mn | P | S | Cu | N |
| 0.170 | 1.400 | 0.040 | 0.040 | 0.550 | 0.012 |

Due to its properties, structural steel S235JR is used in the fabrication of welded, load-bearing, dynamically loaded structures, fatigue loaded, etc [37–40]. It is also used in the production of machine elements and equipment such as bodies, wheels, and platforms and load-bearing elements of lifting devices such as load-bearing beams, main girders, booms, and everywhere where welding is necessary.

2.2. Geometry of joints
The subject of the research was to test joints welded with the MMA method. The geometry of the samples used for mechanical testing were length = 100 mm, width = 30 mm, thickness = 3 mm. There were 6 different types of joints performed:

- butt joints (Figure 1);
- overlap joints with a single weld (Figure 2);
- overlap joints with double welds (Figure 3);
- overlap joints with spot welds (Figure 4);
- overlap joints with hole welds (Figure 5);
- double-flanged seam (Figure 6).

For the tests, 8 test samples of each type were made.
2.3. Welded joint technology
To carry out the tests, weldments were made using the MMA process, the 111 methods (numbered designation according to the PN-EN ISO 4063:2011 standard [41]). Preparation of joints started with appropriate preparation of sample surfaces. In the beginning, the resulting irregularities and burrs left after the process of cutting samples from the sheet were removed. For this purpose, a wavy wire brush was used, mounted on a drill. Additionally, in the samples intended for making overlap joints with a hole joint, holes were made with the dimensions as shown in Figure 4 and Figure 5. The holes were made on the OPTIMUM B20 column drilling machine with the HSS ø 6 mm drill bit, which ensures the repeatability of the operation. Joints were made in workshop conditions, at an ambient temperature of 24°C ± 2°C with an air humidity of 24% ± 2%. The joints were made using the method of welding with a coated electrode using a welding transformer ETd-250-M with a rutile electrode ø 3.2 mm. The used welding transformer type ETd-250-M with continuous direct current regulation is usually used for manual welding.

Figure 1. Shape and dimensions of the butt joint: l = 100 mm, g = 3 mm, b = 30 mm, lz = 12 mm, lc = 201 mm.

Figure 2. Shape and dimensions of an overlap joint with single weld: l = 100 mm, g = 3 mm, b = 30 mm, lz = 10 mm, lc = 190 mm.

Figure 3. Dimensions and shape of overlap joint with double welds: l = 100 mm, g = 3 mm, b = 30 mm, lz = 10 mm, lc = 190 mm.
Figure 4. Shape and dimensions of an overlap joint with spot welds: \( l = 100 \text{ mm}, \ g = 3 \text{ mm}, \ b = 30 \text{ mm}, \ a = 12 \text{ mm}, \ c = 24 \text{ mm}, \ lz = 30 \text{ mm}, \ lc = 170 \text{ mm}.

Figure 5. Dimensions and shapes of the overlapping joint – hole welds: \( l = 100 \text{ mm}, \ g = 3 \text{ mm}, \ b = 30 \text{ mm}, \ a = 7 \text{ mm}, \ c = 12 \text{ mm}, \ lz = 30 \text{ mm}, \ lc = 170 \text{ mm}.

Figure 6. Shape and dimensions of joint with double-flanged seam: \( l = 100 \text{ mm}, \ g = 3 \text{ mm}, \ b = 30 \text{ mm}, \ lz = 6 \text{ mm}, \ lc = 180 \text{ mm}.

After the welded joints were made, they were then subjected to destructive strength tests. These tests were carried out on the Zwick/Roell Z150 strength machine in accordance with standard PN-EN ISO 12996:2013-12 [42].

3. Test results
Figure 7 shows the results of the research. The graph shows the average values of the destructive force of welded joints being tested and the standard deviation value in the form of error bars. The presented analyses were performed in the Statistica program.
From the results obtained, it can be noticed that the highest destructive force was obtained with double weld overlap joints. The value of this force was 37 367 N. The highest repeatability of results was also obtained for these samples – a standard deviation of 0.82%. The lowest destructive force and at the same time the lowest repeatability of results were obtained in the case of side-welded joints. In this case, the destructive force was 8 603 N and the standard deviation was 23.47%. The difference between these cases was more than 4 times. At this point, it is also worth noting the type of specimen destruction during the strength test.

![Graph showing destructive force of welded joints](image)

**Figure 7.** Results of the average destructive force of welded joints.

As a result of the tensile testing in all overlap joints with double welds, the parent material flowed in the area outside the weld, while the weld itself had no visible cracks. It, therefore, follows that this type of welded joint has a higher strength than the strength of the parent material, S235JR. In the case of a joint with a double-flanged seam, in all cases, the joint was destroyed in the weld area. A crack appeared in the area of the heat input.

However, for a comprehensive evaluation of the results presented, a statistical analysis of the results is necessary. To begin with, it was checked whether the assumption of normal distribution (Shapiro-Wilk test) and homogeneity of variance (Levene test) was met. The results of the conducted tests are presented in Table 3 and Table 4. Statistical analysis was performed with the assumed confidence level $\alpha = 0.05$.

**Table 3.** Results of the Shapiro-Wilk test of average values of welded joints destructive force.

| Type of welded joint          | Shapiro-Wilk statistics W | Probability level p | Normality of distribution |
|------------------------------|---------------------------|---------------------|---------------------------|
| butt joints                  | 0.975806                  | 0.701723            | Yes                       |
| overlap joints with a single weld | 0.877530                  | 0.317177            | Yes                       |
| overlap joints with double welds | 0.964286                  | 0.636886            | Yes                       |
| overlap joints with spot welds | 0.971568                  | 0.676418            | Yes                       |
| overlap joints with hole welds | 0.825653                  | 0.177336            | Yes                       |
| double-flanged seam          | 0.995096                  | 0.866149            | Yes                       |
The analysis of the compatibility of the empirical distribution with the normal distribution by the Shapiro-Wilk test did not reject the hypothesis of the normal strength distribution of the tested welded joints for the joint geometries analysed.

Compliance analysis of the empirical distribution with the normal distribution examined employing the Shapiro-Wilk test did not reject the hypothesis of the normality of distribution of the welding joints’ strength for the examined geometries joints (p>α). Another stage of the study was to check the variance homogeneity with the use of the Levene’s test, which results are presented in Table 4.

### Table 4. Variance homogeneity Levene’s test.

|                      | SS Effect | df Effect | MS Effect | SS Error | df Error | MS Error | The value of Levene’s test statistics | Level p for Levene’s test |
|----------------------|-----------|-----------|-----------|----------|----------|----------|---------------------------------------|--------------------------|
| Destructive force    | 7516160   | 5         | 1503232   | 11582822 | 12       | 965235.2 | 1.557374                             | 0.244906                 |

The Levene test did not reject the hypothesis of equal variance. Therefore, ANOVA statistics have been started to check the influence of the geometry of the welded joints on the destructive force value of the welded joints. Therefore, a parametric Tukey HSD test was carried out in order to interpret and compare the results more accurately. The results of this test are shown in Table 5.

### Table 5. The post hoc Tukey’s test designating homogenous groups.

| Type of welded joint                  | Average destructive force [N] | No. of the homogeneous group |
|--------------------------------------|--------------------------------|-----------------------------|
| overlap joints with double welds     | 37 366.67                     | ***                         |
| overlap joints with a single weld    | 30 400.00                     | ***                         |
| butt joints                          | 29 000.00                     | ***                         |
| overlap joints with spot welds       | 23 666.67                     | ***                         |
| overlap joints with hole welds       | 15 600.00                     | ***                         |
| double-flanged seam                  | 8 603.33                      | ***                         |

Based on the obtained results, ANOVA has revealed significant differences between double weld overlap joints, overlap joints with a hole weld, and edge weld joints. No significant differences were observed only between single weld overlap joints and butt joints as well as between butt joints and overlap joints with spot welds because they are within two homogeneous groups.

### 4. Conclusions

The research was conducted on the influence of the geometry of welded joints of S235JR steels on their strength properties analysed in terms of destructive force. There were 8 joints each for 6 types of welded joint geometries: butt joints, overlap joints with a single weld, overlap joints with double welds, overlap joints with spot welds, overlap joints with hole welds, and double-flanged seam. Based on the research, it was noted that:

- the highest average destructive force was obtained with double welded overlap joints;
- the lowest average destructive force was obtained in the case of joints with double-flanged seam;
- the most reproducible results were obtained with double weld overlap joints;
- the least repeatability of the results was obtained for the joints with double-flanged seam;
average destructive force in the case of single weld overlap and butt joints, as well as butt and overlap joints with a spot weld, did not differ significantly with the assumed level of significance $\alpha=0.05$.

In summary, it can be concluded that the most stable constructions are those in which the joints are made to double weld overlap. However, the nature of the structure does not always allow for overlapping joints, in which case it is better to make a butt joint than, for example, a joint with a double-flanged seam.

It can be concluded that the change of construction factors in the process of establishing assembly joints, which include welded joints, has a significant impact on the strength properties of such joints. This aspect should always be considered when designing and subsequently making such joints in physical structures. Where the joint is required to carry certain loads and its value is known, and other methods of bonding are avoided, welding technology may be used to join structural steel sheets.

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