WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.153336

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 1 2025

 pp. 311 –326

Research paper

Assessment of resistance spot welding process quality using modal analysis

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Abstract: The resistance spot welding is one of the main methods used to join thin-walled metal parts, while a number of factors adversely affect the process and thus the quality of the connections made. This article presents the study results of the possibility of applying modal analysis in the quality examination of welded parts by detecting the missing weld. It was aimed to determine this kind welding process imperfections influence on modal shapes and frequencies by the study of the dynamic properties of welded elements in the frequency domain. The research included real and numerical tests. The proposed testing method for spot welded constructions is a scientific novelty in the world, but the investigation results indicated, that the modal analysis may find application in detecting welding defects such as the lack of the welds. To assess the quality of the numerical models, the results obtained in the simulation and experimental test results were compared. The analysis involved the first five modes. The mode shapes in relation to the first five modal frequencies identified using the FEM analyses and the experimental tests was consistent with respect to element distortion. The differences indicate the satisfactory conformity of the numerical simulation results with the experimental test results. The article fundamentally demonstrates the applicability of the above-mentioned method to analyse the performance of all welds at once.

Keywords: FEM, modal analysis, quality control, resistance spot welding, weld quality

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1. Introduction

The resistance spot welding is one of the main methods used to join thin-walled metal parts in many industrial sectors e.g. automotive, electrical engineering, home appliances, aerospace. Resistance welding method has been known for more than 145 years and continues to be developed. The beginning of welding technology dates back to 1877, when Elihu Thomson made an accidental yet ground-breaking discovery involving the flow of a high current through metal parts, resulting in the generation of heat (Joule), which ultimately created a "welded" joint [1]. Resistance welding has three main advantages of both practical and economic nature, these are: (i) no need for additional material [2, 3], (ii) short welding current flow time of approximately 200 ms, (iii) low energy cost per welded joint (about 0.1 US cents) [4]. The information presented above applies to double-sided overlap spot welding of 1 mm thick sheets.

Despite the many years since this technology was covered, it is still widely used in the automotive industry. It is even considered a key joining process in this industry. In a modern vehicle there are about 2000–5000 spot welds [5–8]. Given the large number of welded joints, appropriate quality control methods are required. As in any technological process, there are many dependent and independent (accidental) factors that have an adverse effect on the welding process and thus on the quality of the connections. Therefore, in order to ensure the quality and repeatability of the process, it is necessary to precisely and repeatably control the parameters of the welding process, but also to monitor, control, analyse and evaluate them [9–11].

New and continuously developed quality control methods are used during and after the welding process. During the process, for example, the following are controlled: i) electrical parameters [12, 13], ii) technological parameters (clamping force and displacement of electrodes) [12, 14, 15], iii) weld nugget dimensions [16, 17]. However, these methods require the installation of multiple sensors on the welding machine, and the performance of these sensors determines the accuracy and efficiency of the measurements, which affect the result regarding the quality of welded joints. Automotive industry requirements of inspecting each weld increases the inspection time (thus production time) and requires complex measurement instrumentation (cost, possibility of damage to sensors), while the novelty presented in the article will enable the use of faster and universal and comprehensive identification (examination of the entire structure – all welds at once) and reduce the risk of damage to sensors, since the proposed method can ultimately use non-contact laser sensors.

What remains unchanged is the fact that for responsible joints, whose faulty workmanship and thus poor quality can cause material losses or can be a threat to health and life, appropriate process control is required. The best method is non-destructive and that can cover 100% of the manufactured products. Important is the reliability of the method and the time of execution of the test. This challenge is met by the proposed modal analysis methodology applied to a metal structure in which welded joints are used. Because of the novelty of this methodology, this article presents the possibility of applying the above method to assess the quality of welded joints for basic cases, that is the absence of spot weld. The authors are currently working on the possibility of applying this method to more complex welded structures. The planned implementation of the test method for welded structures will certainly require individual analysis of the structure's natural vibration behaviour each time. This will be due to the geometry and material properties, while the idea of the article was to develop a method, which in itself is a total that requires detailing each time for a given structure.

The modal analysis for studying vibration and dynamic behaviour of structures allows identification and characterization of natural vibrations. Natural vibrations, as natural oscillations of a structure, occur around its static equilibrium and are characterized by their frequency, shape and damping. Such knowledge is extremely important in the design and optimization of a structure, especially in terms of its safe operation [18–24]. Modal analysis is also the object of research involving its use in monitoring the health of a structure by identifying irregularities in its operation in terms of its vibrations [25–28]. Experimental studies are often supported by numerical analyses [29, 30], also in terms of comparing the natural vibration of damaged and undamaged structures [31–34].

The intention of the authors was to analyse "modal parameters" for the detection of weld failure in the manufacturing process. If there are clear differences in the measured signals and correlation of element waveforms with non-conformities of welded joints, it is reasonable to assume that the non-conformities may be reflected in the measured modal parameters. If "Yes" then welding technology specialists would acquire a new tool, a non-destructive method, for quality control of welded joints. In addition to the required accuracy of measurements, an important aspect in the implementation of new solutions for identifying product defects is their low impact on the production processes, and its implementation should be economically reasonable [35, 36]. If modal analysis will be used, it will be associated with an additional and short step involving excitation of the element and measurement of accelerations using non-contact methods [37], and then compare the results to the reference values measured for a properly welded component. Therefore, due to the available accurate and non-contact methods for carrying out modal analysis, the aspect of the integration into the manufacturing process can also apply to high-volume production.

2. Preparation of resistance spot welded joints

Spot welding was performed using a stand equipped with a PMS 14-6MF inverter welding machine having a frequency of 1000 Hz, a nominal power of 250 kVA, a maximum short circuit current of 100 kA and an electrode force of up to 12 kN. The stand was also provided with a portable computer featuring an XPegasus Gold software programme (version V4.1.16). The welding machine software enabled the recording of welding current and voltage as well as electrode force and displacement. The welding stand is presented in Fig. 1.

Test sheets made of steel grade DC04 had dimensions of 150 mm × 50 mm × 1.5 mm. The welding process was performed using a set of electrodes made of material grade A2/2 (CuCrZr) in accordance to the ISO 5182. The electrodes had flat tips and a diameter of 6 mm.

A criterion governing the adjustment of technological parameters was to obtain the nominal weld nugget diameter and the expulsion-free weld (geometric imperfection in accordance with PN EN-ISO 6520-2: P612 – expulsion) [38].

The nominal diameter of the weld nugget (with respect to the plate thickness of 1.5 mm) is adopted by various research centres in the range of 3.5 mm to 6.0 mm [39]. In this publication, the nominal diameter of the weld nugget is assumed in accordance with recommendations [12, 13] and it was calculated based on the thickness of welded sheets:

$$\phi = 5\sqrt{d} \tag{2.1}$$

where: ø – nominal diameter of the weld nugget, d – sheet thickness.

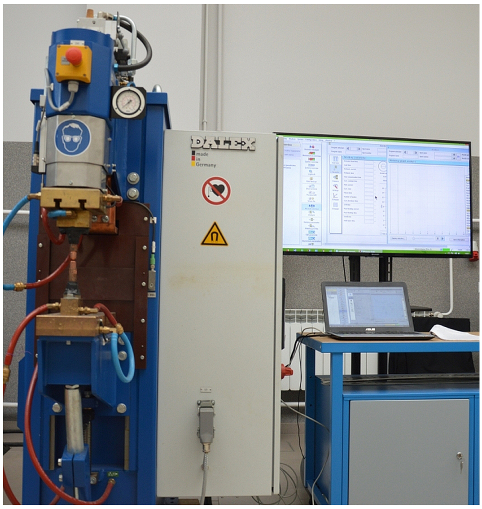
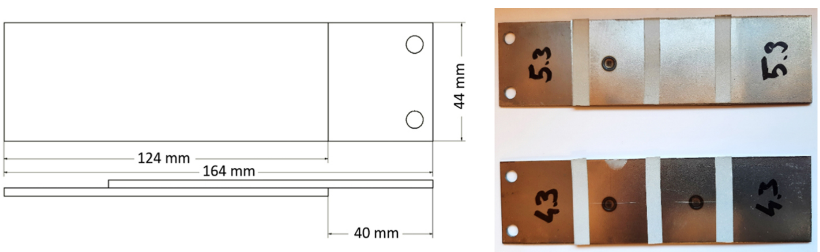


Fig. 1. Welding stand equipped with the PMS 14-6MF inverter welding machine and the XPegasus system

The specimens for presented investigation were made of two steel sheets joined using the spot welding method. The geometry of the specimens and the welded specimens are presented in Fig. 2. The tests involved the preparation of two types of specimens – welded correctly and welded with defect. The correct welded specimen consisted of two spot welds. In the incorrect welded specimen one spot weld did not exist. The purpose of the above-presented preparation of the specimens was the simulation of the lack of spot weld during the production process. The welds were made using parameters as follows: value of welding current 10.0 kA, welding current flows time 200 ms and electrode force 3.5 kN.



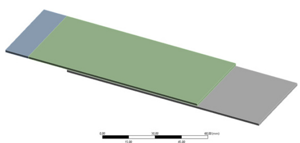
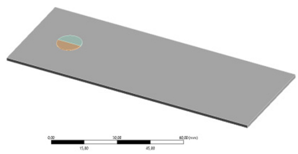
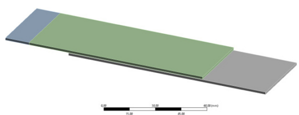
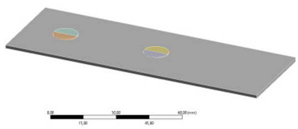
(a) (b)

Fig. 2. Geometry (a) and specimens (b) of spot welded elements

3. Modal analysis of resistance spot welded elements using finite element method

The investigation of the influence of the lack of spot weld on the modal frequencies and distortions was carried out using the FEM. The FEM modal analysis involved the preparation of two models which contained one or two welds Table 1. A properly welded element contained two welds, whereas a deficient element contained one weld (instead of two).

Table 1. Geometry of FEM models of the welded elements

Number of welds	Main view	View without the upper sheet
1		
2		

The geometry-based mesh of finite elements was made of first-order bodies (C3D8R) characterised by appropriate density in accordance with FEM rules and the lack of disqualification in accordance with the criterion of the Ansys software used for structural analyses. The models included 34 000 elements with attributed material properties of steel grade DC04. Because of the limitations of the modal analysis, which is a linear analysis, it was not possible to take into account forces of friction and contact between the areas of the sheets which were not joined permanently. The joints between the upper sheet and the weld as well as between the lower sheet and the weld were used as the boundary condition of the contact, joining the elements permanently. The welded elements were clamped by fixing the nodes of the upper sheet fragment on the upper and the lower side in X, Y and Z direction as indicated in Fig. 3.

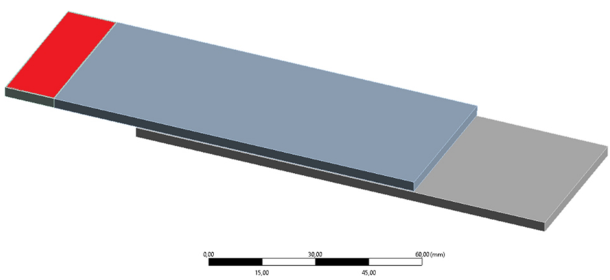
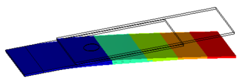
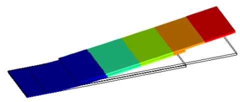
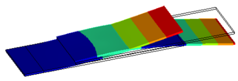
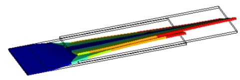
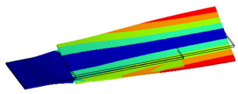
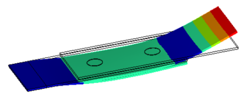
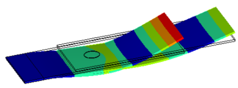
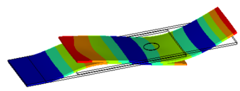
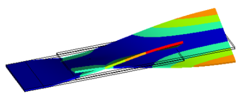
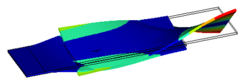
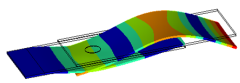
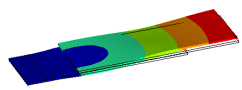
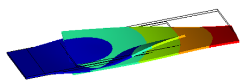
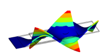
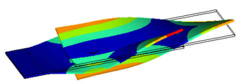
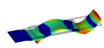
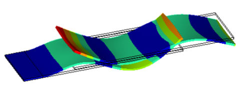
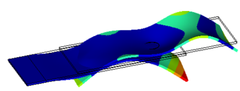
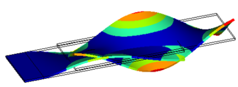
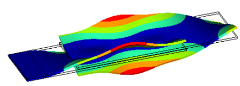


Fig. 3. Clamping boundary condition marked red – X, Y and Z direction fixing of the nodes

The models were used to simulate the modal tests to determine the first ten modal frequencies and corresponding mode shapes. The test results are presented in Table 2. The comparison of the simulation results involved the determination of the matrix of the MAC coefficient in relation to the first ten modes.

Table 2. Results of the simulated modal tests

1 weld			2 welds		
Mode no.	***f*, Hz**	**Shape**	**Mode no.**	***f*, Hz**	**Shape**
1	49.6		1	52.4	
2	185		2	355	
3	339		3	389	
4	446		4	766	
5	649		5	996	
6	768		6	1374	
7	1061		7	1740	
8	1222		8	1968	
9	1486		9	2440	
10	1775		10	2623	

The value of MAC (modal assurance criterion) is one of the most commonly used correlation measures in relation to modal vectors [40,41]. The aforesaid value makes it possible to conveniently quantify the similarity of two modal vectors in the scale of 0 to 1, where a value close to unity indicates the perfect match. The MAC value for actual eigenvectors can be estimated in accordance with:

$$\text{MAC}_{ij} = \frac{\left(\hat{\phi}_i^T \phi_j\right)^2}{\left(\hat{\phi}_i^T \phi_i\right)\left(\hat{\phi}_j^T \phi_j\right)} \tag{3.1}$$

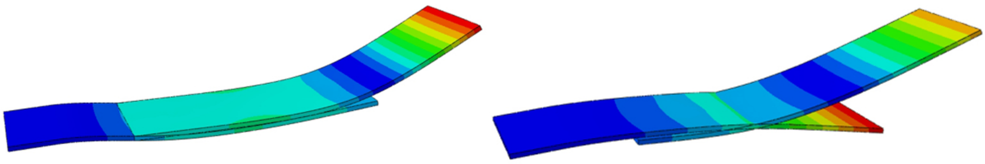
where: $\hat{\phi}_i$ – the i-th modal vector, ϕ_j – the j-th referenced modal vector.

Since MAC values are the result of the normalized scalar product of two eigenvectors, the scaling of mode shapes being compared can be ignored. This feature makes MAC particularly easy to apply in cases where modal vectors originate from a different data acquisition system [42]. An MAC estimation performed for a range of modal vectors results in the obtainment of a MAC matrix providing the overview of the correlation of two modal matrixes. In such a case, high values at the diagonal of the MAC matrix indicate the high correlation of modal matrixes. High off-diagonal values of the MAC imply discrepancies in the modal parameters of two separate sets of modal data [43]. The comparison of the coefficients is presented in Table 3.

Table 3. MAC matrix of the first ten modes of the investigated specimens, shades of green marked the MAC table values from the lowest (light shade) to the highest (dark shade)

	***f*, Hz**	**1 weld (deficient specimen)**									
f, Hz	MAC	49.6	185	339	446	649	768	1061	1222	1486	1775
2 welds (correct spot welded joint)	52.4	0.99	0.00	0.19	0.03	0.00	0.00	0.00	0.17	0.33	0.00
	355	0.00	0.00	0.58	0.33	0.00	0.00	0.00	0.31	0.21	0.00
	389	0.00	0.98	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.04
	766	0.23	0.00	0.20	0.12	0.00	0.00	0.00	0.02	0.44	0.00
	996	0.00	0.05	0.00	0.00	0.53	0.00	0.14	0.00	0.00	0.09
	1374	0.09	0.00	0.22	0.83	0.00	0.00	0.00	0.00	0.07	0.00
	1740	0.00	0.00	0.00	0.00	0.03	0.56	0.14	0.00	0.00	0.06
	1968	0.00	0.02	0.00	0.00	0.33	0.12	0.28	0.00	0.00	0.29
	2440	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.81	0.52	0.00
	2623	0.00	0.03	0.00	0.00	0.06	0.06	0.74	0.00	0.00	0.15

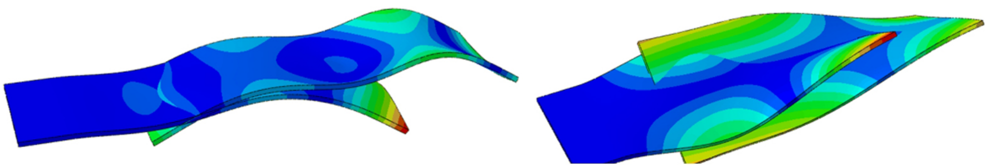
Based on the MAC matrix comparison of the correct joint with the deficient one, it could be concluded that the first bending mode was not affected by the lack of the second spot weld from the modal shapes point of view or from the frequency point of view. In terms of rotational modes (mode 2 concerning the correct welded joint design and mode 3 concerning the deficient one), the modal shape was affected (MAC value being 0.58) but eigenfrequency values stood at similar levels (i.e. 339 Hz and 355 Hz). On the other hand, the higher order bending modes, where the two welded metal sheets oscillated in opposite directions (e.g. mode 3 concerning the correct design and mode 2 related to the deficient one), remained similar in terms of mode shapes Fig. 4, yet differed significantly as regards natural frequency (389 Hz vs 185 Hz). This type of difference in the dynamic behaviour of the structure might be particularly useful for the detection of the defective spot welded joint as the pair of the modal vectors is easy to identify (owing to MAC values) and the reduction of eigenfrequency clearly indicates the loss of stiffness.



(a) (b)

Fig. 4. Comparison of (a) mode 3 (correct specimen) and (b) mode 2 (deficient specimen)

It should also be noted that relatively complex mode shapes appearing at higher frequencies (and being the combination of bending and twisting) remained similar in terms of mode shapes as long as their mode nodes aligned with the location of the spot welds. The aforesaid case was exemplified by the 9^{th} mode, related to the correct welded joint, and the 8^{th} mode, related to the deficient welded joint Fig. 5. Nevertheless, the reduction of the natural frequency value remained characteristic of the deficient specimen also for this type of mode.



(a) (b)

Fig. 5. Comparison of (a) mode 9 (correct specimen) and (b) mode 8 (deficient specimen)

4. Experimental modal analysis of resistance spot welded elements

In order to confirm the correctness of the numerical modal analysis it was necessary to perform experimental tests. The test stand consisted of the following elements Fig. 6. The vibration tests of the specimens were performed in accordance with the following procedure:

- mounting a specimen on the support attached to the shaker (torque: 4 Nm),
- defining scanning geometry by means of scanning vibrometer software,
- excitation of the specimen and the performance of simultaneous vibration measurements at previously defined points and at the reference point,
- computation of a frequency response function (FRF) using estimator H1,
- identification of natural frequencies,
- comparison of specimen natural frequencies and corresponding mode shapes.

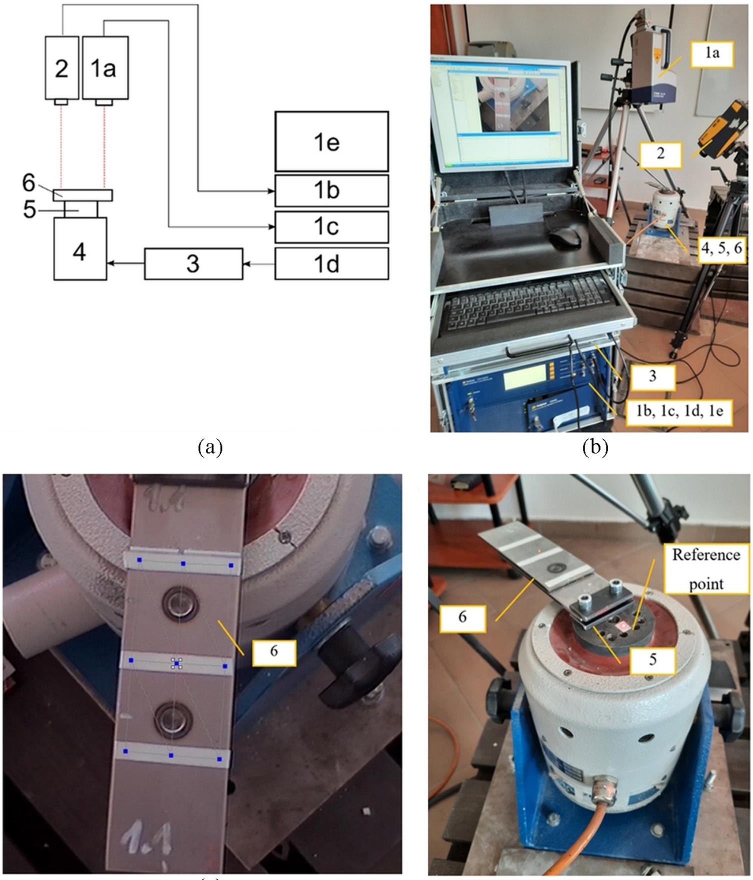


Fig. 6. Diagram of measurement setup: (a) and the test bench (b) with one of the tested specimens (d) and the arrangement of measurement points (c); 1. PSV-400 scanning laser vibration system (Polytec) featuring: a. scanning head, b. vibration controller, c. junction box, d. signal generator, e. PC provided with software dedicated to measurement control and signal analysis, 2. PDV-100 laser Doppler vibrometer (Polytec), 3. BAA 500 power amplifier (Tira), 4. TV51120 modal shaker (Tira), 5. support of a tested specimen, 6. tested specimen

The vibration measurement was performed within the 0–8000 Hz frequency band. The frequency band-related assumption was based on the shaker specification. The excitation signal was random noise taken from a generator built in the measurement system. The period of excitation was synchronized (by the measurement software) with measurements at previously defined points. The estimation of frequency response function (FRF), using estimator H1, was performed in relation to each measurement point. The level of excitation was set arbitrarily (to avoid overloads in measurement channels). Because of the application of the reference signals (in relation to the estimation of frequency characteristics), it was not necessary to set specific vibration levels. The investigation involved the testing of three specimens in relation to each type (1 weld or 2 welds) of the welded joint.

5. Results of experimental tests

The modal tests of the specimens resulted in the obtainment of a number of averaged frequency response functions (FRF). The FRFs were used to perform the analysis in respect of the repeatability of tests in relation to the same type of specimens and differences between types of specimens.

Figure 7 presents the comparison of the FRFs determined in relation to the three specimens containing two welded joints. It is possible to observe a significant correlation between natural frequencies within the 0–2300 Hz frequency band. Above a frequency of 2300 Hz it is possible to notice high ambiguity in the characteristics curves. For this reason, values above 2300 Hz were not taken into account in the further FRF analysis. To assess compliance and repeatability, the characteristics of all tested specimens were compared and presented in the Fig. 7 and Fig. 8.

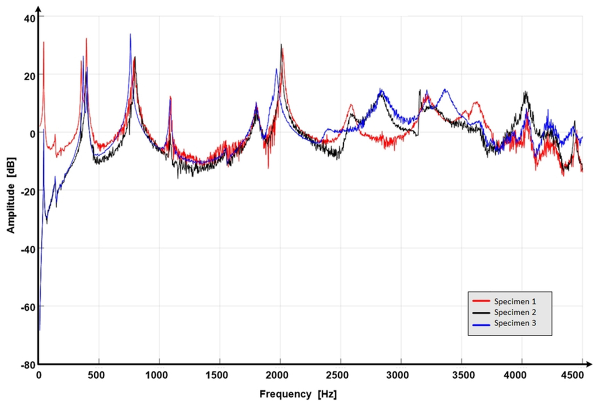


Fig. 7. Specimens with two welds in the 0–4500 Hz frequency band

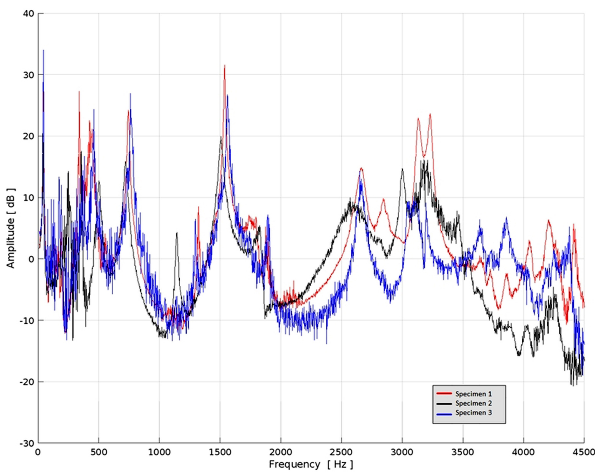


Fig. 8. Specimens with one weld in the 0–4500 Hz frequency band

In order to assess the effect of the number of welds (one or two welds), the selected samples in Fig. 9 were compared. The test results led to the conclusion that it is possible to detect an imperfection in the welding process involving the absence of one weld, changes are noticeable in the frequency band up to 2300 Hz. For the sample with two welds, high amplitude components at 1090 and 2020 Hz were found, while no components at these frequencies were found in the sample with one weld. The opposite case was also found, a high amplitude peak occurred at 1538 Hz in the sample with one weld, which was not found at this frequency in the sample with two welds. In the higher frequency range, due to the large influence of the testing process, the impact of quality-related errors could not be clearly assessed.

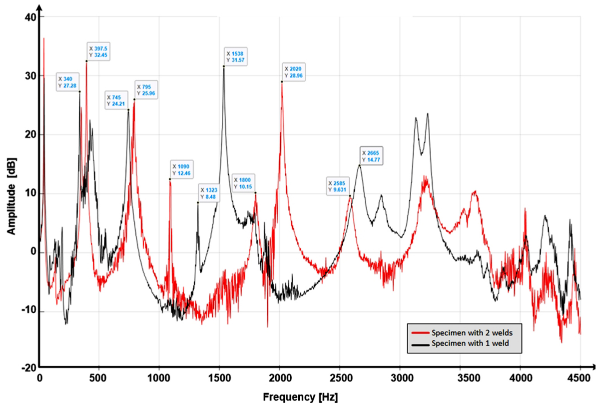


Fig. 9. Comparison of specimens with 2 welds or 1 weld in the 0–4500 Hz frequency band

6. Comparison of simulation and experimental test results

To assess the quality of the numerical models, the results obtained in the simulation and experimental tests were subjected to comparison presented in Table 4 and Fig. 10. The analysis involved the first five modes. The mode shapes in relation to the first five natural frequencies

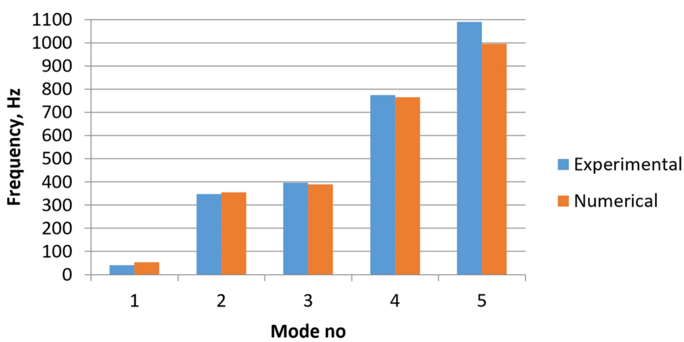
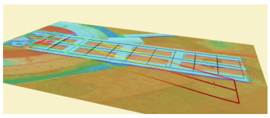
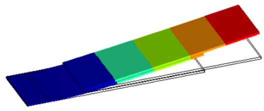
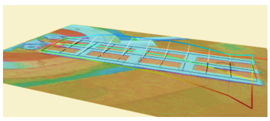
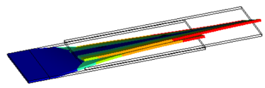
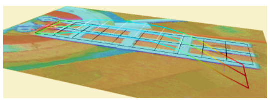
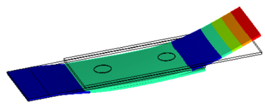
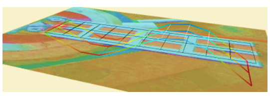
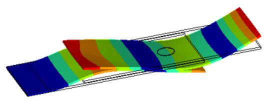
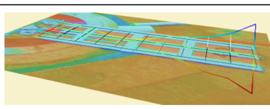
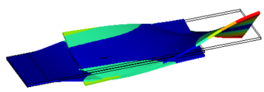


Fig. 10. Comparison of the experimental and the numerical test results in relation to the first five eigenvibration-related frequencies

identified using the FEM-based numerical analyses and the experimental tests was consistent with respect to element distortion. In relation to the first mode, a percentage difference between the numerical and the experimental test results amounted to 25%, i.e. 12 Hz. In relation to the second and the third mode, a percentage difference between the numerical and the experimental test results amounted to 2%, i.e. 7 Hz and 8 Hz. In relation to the fourth mode, a percentage difference between the numerical and the experimental test results amounted to 1%, i.e. 9 Hz, whereas in relation to the fifth mode, a percentage difference between the numerical and the experimental test results amounted to 9%, i.e. 95 Hz. The above-presented differences indicate the satisfactory (good) conformity of the numerical simulation results with the experimental test results.

Table 4. Comparison of the frequencies and the mode shapes obtained in the experimental and the numerical modal analysis of the specimens with two resistance spot welds

	2 welds – experimental		**2 weld – numerical**	
Mode no.	***f*, Hz**	**Shape**	***f*, Hz**	**Shape**
1	40.4		52.4	
2	348.4		355.0	
3	396.9		389.0	
4	775.0		766.0	
5	1090.6		996.0	

7. Conclusions

Based on the study of thin-walled resistance spot welded metal structures, the modal analysis method may find application in detecting welding defects such as the lack of the welds. Confirmation of the above possibilities, however, requires further research.

The successful verification of the quality of welded joints depends on numerous factors, including, among other things, the shape of the metallic structure, the location of welds, the area of excitation or the area of measurement. The complexity of the issue is caused by modal characteristic of element that among others depends on geometry and material. The more rigid is the structure, the less accurate are the results and, vice versa, the less rigid (more flexible) is the structure, the effectiveness of the method is the higher. In relation to highly correlated mode pairs (having a high MAC value), the reduction of the natural frequency value was a clear indication of the progressing loss of stiffness and, consequently, of a joint failure. Such knowledge and test methodology are key to the development of measurement instrumentation for quality control of welded structures.

The validation of the FEM models revealed that the latter were characterised by satisfactory consistency with the results obtained in the experimental tests. The comparative analysis of the results obtained in the experimental tests with those obtained in the FEM tests revealed that the most accurate results were obtained where frequency was restricted within the range of 0 Hz to 2300 Hz. In view of the foregoing, the FEM modal analysis can be used successfully in the development of the assumptions for the preparation of the test method, which will be used to detect the lack of the welds.

The results of deformations and natural frequencies indicate that the differences are significant. For more complex structures, a measurement solution involving a larger number of measurement points will be required, which can be defined by using numerical methods and real tests. In turn, this is related to the individual (for each construction) development of the conditions of the proposed test method due to the construction geometry and material properties differences.

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Ocena jakości procesu zgrzewania punktowego za pomocą analizy modalnej

Słowa kluczowe: analiza modalna, jakość zgrzeiny, kontrola jakości, MES, punktowe zgrzewanie oporowe

Streszczenie:

Punktowe zgrzewanie oporowe jest jedną z głównych metod stosowanych do łączenia cienkościennych elementów metalowych, przy czym szereg czynników wpływa niekorzystnie na proces, a tym samym na jakość wykonanych połączeń. W artykule przedstawiono wyniki badań możliwości zastosowania analizy modalnej w analizy jakości zgrzewanych elementów w aspekcie wykrywania brakującej zgrzeiny. Celem było określenie wpływu tego typu niedoskonałości procesu zgrzewania na postać i częstotliwości drgań własnych poprzez badanie w dziedzinie częstotliwości właściwości dynamicznych elementów zgrzewanych. Badania obejmowały testy rzeczywiste i analizy numeryczne. Zaproponowana metoda badania konstrukcji zgrzewanych jest nowością naukową na świecie, a wyniki badań wskazały, że analiza modalna może znaleźć zastosowanie w wykrywaniu wad zgrzewalniczych takich jak brak zgrzein. Skuteczna weryfikacja wykonania danej zgrzeiny w zgrzewanym elemencie zależy od wielu czynników, w tym m.in. materiału i kształtu konstrukcji, lokalizacji zgrzein, miejsca wzbudzenia i pomiaru podczas jej badania. W związku z tym każda badana geometria będzie wymagać opracowania indywidualnych założeń wymuszeń i pomiaru, natomiast ogólne założenia stosowania analizy modalnej pozostają niezmienne. W celu oceny wyników modeli numerycznych, porównano wyniki uzyskane w symulacji i wyniki badań eksperymentalnych. Analiza wykazała, iż postaci drgań własnych w odniesieniu do pierwszych pięciu częstotliwości zidentyfikowanych za pomocą analiz MES i testów eksperymentalnych były zgodne pod względem odkształceń elementów. Różnice wskazują na zadowalającą zgodność wyników symulacji numerycznej z wynikami testów eksperymentalnych, a tym samym zasadne jest stosowanie MES w opracowaniu założeń do opracowania stanowiska pomiarowego konstrukcji zgrzewanych. Artykuł zasadniczo demonstruje możliwość zastosowania wyżej wymienionej metody do analizy jakości wszystkich spoin jednocześnie.

Received: 2023-10-16, Revised: 2024-02-20