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# Enhancing Demolition Works Safety: Integrating Numerical and Experimental Methods for Structural Failure Prevention in Remote-Controlled Demolition Robots.



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# Highlights

- Method from FEM and test data proposed to avert machine structural failure.
- The actual dynamic loads and the counting of load cycles problem solved.
- The FEM model with test data outperforms classical methods in fatigue assessment.
- The proposed method allows to prevent uncontrolled damage to the machine structure.

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### 1. Introduction

Due to technological progress, the offer of demolition robots available on the market continues to expand [1]. The once popular wrecking ball has been replaced by much more efficient demolition excavators. Recently, demolition robots have also appeared on this list [2,3,4]. Because of their excellent mobility and zero emission operation, demolition robots are increasingly used during demolition works. They can reach places that larger machines, such as excavators, cannot. Because they are remote-controlled, the operator can safely operate the machine without

Abstract

The paper presents an approach that combines numerical and experimental techniques to evaluate the possibility of failure prevention of the structure of demolition robots. Based on a real example of the machine, the possibility of application and development of the proposed method was presented. The main problem when designing this type of machine is the negligible knowledge of how dynamic loads act during operation and how many times they appear. Underestimating the loads and their cycles when designing these types of machines can cause them to become damaged quickly. The method presented in the article allows to solve the problem of determining the key parameters needed in the evaluation of this type of construction such as loads, but also allows to determine the number of load cycles, which is particularly important for fatigue. The result presented in the article is a method that allows determining the fatigue of the structure of a demolition machine by combining numerical and experimental techniques.

### Keywords

Finite Element Method, fatigue strength, strain measurements, remotecontrolled machines, demolition works, machine safety

> being directly exposed to a large number of hazardous factors in its working environment. In the case of larger machines, where the operator is directly in the machine cabin, he or she is exposed to greater dangers, such as the machine tipping over during operation [5]. Given the multipart nature of their arms system, which have more degrees of freedom than classic excavators equipped with hydraulic hammers, these new machines can be operated in much more difficult conditions. An example of a demolition robot is shown in Fig. 1.

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Fig. 1. Demolition robot ARE 2.0 [2].

Due to the growing popularity of demolition robots and their construction, which is more complicated than that of classic



excavators, also their failures occurred. Fig. 2 presents examples of damage of the arms system of this type of machines.



Fig. 2. Examples of damage of the arms system: (a) Detachment of part of the arm; (b) The lug deflection and the crack initiation; (c) Failed repair of arm structure; (d) Weld crack.

Uncontrolled damage to the machine, as shown in Fig. 2, can cause downtime but can also be dangerous from the point of view of operator safety. These situations may be caused, for example, by an underestimation of the load assumed during the calculation of the machine during operation or incorrect estimation of load cycles, which significantly affects the correct estimation of fatigue strength of individual parts of the machine. More and more attention is paid to preventing such situations. The paper presents an original approach, in the case of this type of machine, to counteract uncontrolled damage to the machine already at the design stage and during operation. The presented method allows to fully understand the operation of these machines and determine their real loads during operation, which is crucial from the point of view of their safety.

# 2. Contemporary Methodological Approaches

To the correct approach in the case of counteracting uncontrolled damage already at the design stage, it should also be clarified what requirements the machine should meet during operation, so that it does not damage uncontrollably. The main way is to estimate the strength already at the design stage. In this case, various types of numerical techniques can be used, in which the strength of the elements designed for given loads is analyzed. This can be divided into structural strength and fatigue strength. An analysis of structural strength is sufficient for machines that are not subjected to cyclical loads. In the latter case, where cyclical loads are applied, the fatigue of the material and the fatigue strength of the welds are analysed [6,7]. Due to the development of numerical methods, they have become one of the most popular techniques for assessing the strength of carrying structures or the construction of arm systems at the initial design stage. The most popular method is the Finite Element Method [8-11]. In many cases, numerical methods are also used for the assessment of fatigue strength, as shown, eg, in [12-15]. However, there are cases where not all possible load scenarios are foreseen during machine operation and some parts of the machine will be destroyed during operation, as illustrated in Figure 2. To validate the assumed boundary conditions, estimate the maximum loads or verify the accuracy of the numerical model, numerous experimental methods are used, which are described in [16-23]. They can also be used to obtain information on the actual strain of selected points in the

structure. One of the most common methods to measure the value of machine strain is the resistance strain gauge [24]. Attempts have already been made to compare numerical methods with strain gauge measurements and they have been described, for example, in [25,26], but they do not apply to the machine being analyzed. This technique offered the opportunity to perform a preliminary verification of assumptions related to the boundary conditions or the accuracy of the numerical model. In the case of demolition robots, while efforts were made to verify their strength, the state of machine stress in various load cases was not fully illustrated [27,28]. These papers only present the possibility of using a combination of numerical and experimental methods, without explaining which cases are keys for such a construction. Fatigue strength analysis, which is crucial for machines that are subject to significant load changes and perform many cycles, such as demolition robots, was also omitted.

As a result of the analysis of various approaches to the fatigue estimation test in selected machines, there was a definite lack of an unambiguous evaluation method, as well as design guidelines, of demolition robots, which are exposed to loads resulting from the dynamic operation of a hydraulic breaker, as well as performing a large number of load cycles in various configurations. In the case of fatigue assessment, already known methods are used, which are described, for example in [29-33], but it is only a tool to assess fatigue, which needs input data to be able to perform the analysis correctly. In the proposed method, available tools for fatigue assessment are used, along with the available FEM calculation method, which allows for determining the strength of the machine structure. These methods are not very useful in this case without correctly defining the input data. The article draws attention to the problem that occurs in evaluating the fatigue of this type of machine and indicates the path that can be followed to eliminate this problem. The main part of the presented method are tests on a real object, which allow one to obtain the necessary information to correctly conduct fatigue analysis in this type of machines. The article outlines methodologies for selecting measurement points, conducting measurements, and then analyzing and utilizing these results in the assessment of fatigue life of the structure. The final stage of the presented method is the evaluation of the actual fatigue of the structure based on the

measurement data supported by numerical methods. The whole

scheme adopted in the described method is presented in Fig. 3.



Fig. 3. A diagram of the presented method with a specification of the specific contribution.

# 3. Integrated Numerical and Experimental Approach to Demolition Machine Assessment for

The method is presented on the example of the ARE 2.0 demolition machine. Data for the numerical calculations were taken according to the load on the machine. If this method is used for machines of this type, it should be performed for data suitable for the machine being analysed. The results presented in the work aim to demonstrate the usefulness of the presented method for future use in this type of machine and present a solution to the key problem in evaluating the fatigue life of these machines, which is the correct determination of the force acting on the object and the cycles of its application.

# 3.1. Numerical Model of Demolition Machine

In the presented method, which allows to determine the key parameters for assessing the fatigue of this type of machines, numerical FEM models play an important role. In the first phase, it allows, for the classical approach of structural calculations in the static case, to determine the appropriate locations for the strain gauges. Knowledge of the correct placement of the measuring sensors is essential throughout the method. This allows us to eliminate errors in estimating the actual dynamic load of the machine at an early stage. FEM calculations in the presented method are also used for the tested real object to verify the correctness of the assumptions made, such as boundary conditions, but also in the case of assessing the fatigue of the machine structure, due to the input data.

All work related to the preparation of the numerical model, as well as the calculations themselves, was carried out using Abaqus CAE software [34]. For both, the first stage of the work, i.e. the determination of the places for the installation of the measuring sensors, and for the subsequent analyses in the assessment of the fatigue strength of the structure, one FEM model was built. This is possible because of its subsequent verification based on the obtained measurement data. A virtual 3D geometric model was built as an assembly of individual machine components as shown in Fig. 4.



Fig. 4. 3D numerical model of the demolition machine: (a) Front isometric view; (b) Rear isometric view.

Based on the geometric model, a discrete shell model was built. It consisted of 175344 quadrangular elements and 4924 triangular elements, which gave a total number of 201727 nodes. As a result of the defined connections between parts, additional 197235 nodes were generated. The total number of equations in the model was 1161882. An example of a finite element model is shown in Fig. 5. In the numerical model, kinematic pairs were simplified to retain only their actual physical behaviour, such as the connection of individual arms as a rotational pair. This ensured free movement of the pin along its axis and accurately represented its pressure on the cooperating bushing. Due to the lubrication applied in the kinematic pairs of the actual machine, the effect of friction was disregarded in kinematic pairs. Friction in the numerical model was applied only between cooperating structural elements, such as the brackets used for attaching components to the machine frame. A friction coefficient of 0.3 was applied between the interacting elements.



Fig. 5. FEM discrete model of the machine: (a) view of the parts of the arm system; (b) chassis view.

In the case of machines with a multi-arm working system, a certain number of simulation cases must be analyzed so that the assessment of the strength of the structure under a given load can be considered correctly. Many simulation cases are associated with various positions of the multi-arm working system. It is very difficult to carry out analyses for all possible positions with so many degrees of freedom. Therefore, in the presented paper, only a few key positions of the arm system of the machine have been selected, as described in Table 1, and are

shown graphically in Fig. 6. Each position of the machine was treated as a separate numerical simulation. Since the node numbering remained unchanged in the model for different positions and only their positions in space were altered, it became feasible to conduct evaluations for all cases. This strategy enabled the effective use of a model, without the need for the movement of kinematic pairs during simulation, which would have significantly extended the simulation time.

Table 1. Selected cases of machine operation.

Description	Subcase	Case
Vertical walls demolition – maximum position of the arms	P1.1	DI
Vertical walls demolition – minimum position of the arms	P1.2	PI
Ceilings demolition – maximum position of the arms	P2.1	D0
Ceilings demolition – minimum position of the arms	P2.2	P2
Floors demolition – maximum position of the arms	P3.1	Da
Floors demolition – minimum position of the arms	P3.2	P3



Fig. 6. Examples of machine positions used for numerical calculations according to Table 1: (a) Case P1; (b) Case P2; (c) Case P3.

The developed numerical models were subjected to a strength analysis using FEM. The boundary conditions adopted for the analysis are directly related to the stability of the machine (the model is affected by gravity) and the operation of the Epiroc SB202 hydraulic breaker with the following parameters:

- ✓ Hydraulic input power, max 17 kW;
- ✓ Oil flow 35 l/min 65 l/min;
- ✓ Operating pressure 100 bar 150 bar;
- ✓ Impact rate 850 blows/min 1 800 blows/min.

An example of boundary conditions applied in the model for the selected case is shown in Fig. 7.



Fig. 7. Example of boundary conditions in the simulation, where U - translation, F<sub>b</sub> - breaking force.

The numerical model prepared in this way can be used as a basis for determining the location of the installation of the strain gauges and for subsequent fatigue analyses of the structure.

#### 3.2. Strain Measurements on Demolition Machine

The next step involved taking measurements on the structure of the demolition machine. A resistance strain gauges were used to measure the level and range of changes in the strain during machine operation. Subsequently, the strain values obtained were converted into stresses, which in turn were used as a basis in the later part of the work. The conversion was made using the dependence (1) for the quarter bridge circuit, where  $\varepsilon_n$  is

normal strain,  $\varepsilon_s$  is apparent strain,  $\varepsilon_b$  is banding strain,  $V_0$  is the bridge output voltage, and  $V_S$  is the bridge excitation voltage [<u>35</u>].

$$\varepsilon = \varepsilon_n + \varepsilon_b = \frac{4}{k} \frac{V_0}{V_S} - \varepsilon_S \tag{1}$$

Strain gauges with the following parameters were used for the measurements:

- ✓ Resistance -  $350\pm0.2\% \Omega$ :
- ✓ Strain sensitivity factor k - 2.1-2.2;

Strain gauges were installed on the individual arms of the machine in predetermined places, and their examples are shown in Fig. 8.



(a)

Fig. 8. Examples of installed strain gauges: (a) Arm 1; (b) Arm 2.

Fig. 9 shows the machine prepared for operation with the

mounted measuring system.



(a)

(b)

Fig. 9. Demolition robot: (a) General view of the measuring system; (b) View of the measuring device.

The signal in the form of a voltage change depending on the change in the resistance of the strain gauge was recorded using the LMS SCADAS Mobile & Recorder. Since the frequency of the hammer's operation was in the range of 14 to 30 beats per

second, a sampling frequency of 1024 Hz was chosen so as not to lose valuable measurement data. Fig. 10 shows the test site and the machine.



Fig. 10. Machine in operation: (a) Wall demolition – P1; (b) Ceiling demolition – P2.



conversion to stress values over time during machine operation.



Fig. 11. Stress values for wall demolition (P1) over a selected period.



Fig. 12. Stress values for wall demolition (P1) over a selected period - smaller time interval.



Fig. 13. Stress values for ceiling demolition (P2) over a selected period.



Fig. 14. Stress values for ceiling demolition (P2) over a selected period – smaller time interval.







Fig. 16. Stress values for ceiling demolition (P3) over a selected period - smaller time interval.

Due to the large amount of measurement data, only exemplary stress changes over time are presented, which allow us to present the possibility of assessing the correctness of the adopted method.

## 3.3. Verification of Numerical Model Assumptions

To assess the accuracy of the numerical model and the boundary conditions, verification simulations were performed. This will minimise errors in the subsequent strength assessment that allow to assess the probability of machine parts damage. Due to the high sampling value for the selected time interval of the signal, its RMS value [36] shall be determined. The resulting stress values refer to the results of numerical simulations at the locations of the strain gauges on the real object. The verification process, as an example, is presented in Fig. 17 for a single point, while Tab. 2 presents a comparison of the stress values obtained experimentally with those read from the FEM calculations.





Table 2. Stress	values obtained	d by numerica	al calculations	and measurements.

	T1	Τ2	Т3	T4	Т5	<b>T6</b>	T7	T8
FEM [MPa]	31,06	29,17	5,15	4,82	19,82	18,24	57,41	55,39
Measurement [MPa]	29,58	27,81	4,95	4,64	18,86	17,63	56,44	54,23
Error [%]	4,76	4,89	4,04	3,73	4,84	3,46	1,72	2,14
FEM [MPa]	20,04	19,45	6,84	6,67	26,39	24,06	55,34	54,75
Measurement [MPa]	19,11	18,49	6,53	6,35	25,56	23,27	54,62	53,89
Error [%]	4,87	4,94	4,53	4,79	3,25	3,39	1,32	1,60
FEM [MPa]	4,39	4,02	19,41	19,67	55,76	53,26	60,2	59,68
Measurement [MPa]	4,19	3,83	18,62	18,76	53,74	51,62	59,08	58,64
Error [%]	4,56	4,73	4,24	4,63	3,76	3,18	1,90	1,77
-	FEM [MPa] Measurement [MPa] Error [%] FEM [MPa] Measurement [MPa] Error [%] Measurement [MPa] Error [%]	FEM [MPa]      31,06        Measurement [MPa]      29,58        Error [%]      4,76        FEM [MPa]      20,04        Measurement [MPa]      19,11        Error [%]      4,87        FEM [MPa]      4,39        Measurement [MPa]      4,19        Error [%]      4,56	FEM [MPa]      31,06      29,17        Measurement [MPa]      29,58      27,81        Error [%]      4,76      4,89        FEM [MPa]      20,04      19,45        Measurement [MPa]      19,11      18,49        Error [%]      4,87      4,94        FEM [MPa]      4,39      4,02        Measurement [MPa]      4,19      3,83        Error [%]      4,56      4,73	FEM [MPa]      31,06      29,17      5,15        Measurement [MPa]      29,58      27,81      4,95        Error [%]      4,76      4,89      4,04        FEM [MPa]      20,04      19,45      6,84        Measurement [MPa]      19,11      18,49      6,53        Error [%]      4,87      4,94      4,53        FEM [MPa]      4,39      4,02      19,41        Measurement [MPa]      4,19      3,83      18,62        Error [%]      4,56      4,73      4,24	FEM [MPa] $31,06$ $29,17$ $5,15$ $4,82$ Measurement [MPa] $29,58$ $27,81$ $4,95$ $4,64$ Error [%] $4,76$ $4,89$ $4,04$ $3,73$ FEM [MPa] $20,04$ $19,45$ $6,84$ $6,67$ Measurement [MPa] $19,11$ $18,49$ $6,53$ $6,35$ Error [%] $4,39$ $4,02$ $19,41$ $19,67$ Measurement [MPa] $4,19$ $3,83$ $18,62$ $18,76$ Error [%] $4,56$ $4,73$ $4,24$ $4,63$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

The presented method allows to verify the assumptions made in the case of boundary conditions of the simulation. The differences between the numerical results and those obtained from the measurements are mainly due to the simplifications used to build the numerical model. These simplifications are related to, for example, the lack of consideration of the stiffness of hydraulic hoses and the mass of oil flowing in the system, as well as, for example, the lack of information about the exact stiffness of kinematic pairs in the model and other, smaller simplifications, which ultimately affect the accuracy of the entire model. However, these errors do not exceed 5% and it was decided to accept them because they do not significantly affect the results of the entire FEM simulation.

The measurements also allow to estimate the number of overloads occurring during the operation of a hydraulic hammer,

which is impossible in the case of the classic approach of determining the load coming from a hydraulic hammer. In the classical approach, the determined force is applied to the model without considering the dynamic effects, which often leads to an underestimation of the load on the machine, which in turn can lead to its quick failure. In the presented method, the measurements made enable to determine the actual impact of dynamic influences on the machine structure for given operating conditions. When specific measurement points are analysed, the value of the dynamic overload coefficient can be determined for specific hammer strokes. In this case, it is proposed to determine the coefficient as the quotient of the extreme values for specific hammer strokes, as shown in Fig. 18.



Fig. 18. The process of determining the dynamic overload coefficient  $\vartheta_d$  for the selected load cycle.

It is suggested to determine the coefficients for the entire load cycle and then performing a quantitative analysis of the occurrence of a given coefficient value. Determination of the overload factor allows to eliminate the error during the formulation of construction assumptions, resulting from underestimation of the load.

Attention should also be paid to the aspect of counting load cycles during machine operation, which is crucial in assessing the fatigue strength of the structure. By using the measurement data in the presented method, it is possible to obtain information on the number of cycles of machine operation, which allows to obtain a full history and the amount of load acting on the machine. It is not possible to correctly determine the load cycle of the machine without measuring the load under machine operating conditions. The characteristic time intervals, which correspond to the load cycles of the machine, can be observed on the recorded load values of the machine, an example is shown in Fig. 19, and the cycle is marked with intervals and their names are C1, C2... C14.



Fig. 19. Example of determining machine load cycles based on machine load measurement results, where C - cycle,

The results obtained from the measurements show the possibility of their use in the presented method. They allow the initial verification of the assumptions made in the case of the construction of numerical models, the determination of the actual loads acting on the machine, considering the dynamic impact, and also allow the determination of load cycles, which significantly affects the development of the method of assessing the fatigue strength of this type of machines.

# 3.4. Structural Fatigue Assessment

The last step of the presented method is the assessment of the

fatigue of the structure based on a combination of numerical and experimental techniques. FEM numerical models and measurement data, which serve as an input element for analyses, allow to carry out a fatigue analysis of the demolition machine structure to verify it correctly. This prevents uncontrolled damage to the machine, which also improves work safety.

The first step in the fatigue strength assessment is to perform multiple numerical simulations for a validated model, considering the actual measured forces. Examples of the FEA results for several machine positions are shown in Fig. 20.



Fig. 20. Examples of FEA results in the form of Mises stress contours in MPa: (a) - Case P1; (b) - Case P2.

The results of numerical analyses, which are presented in the article, were evaluated on the basis of the guidelines adopted in the case of structural strength according to [29-31], while fatigue strength according to EN 1993-1-9:2005 standard - Eurocode 3: Design of steel structures - Part 1-9: Fatigue [32] according to Hot Spot geometric stress method described by Prof. Adolf F. Hobbacher [33]. Calculations of the fatigue life of structural elements subjected to low cycle fatigue were made

based on the hypothesis of accumulation of fatigue damage according to the Palmgren-Miner hypothesis [<u>37</u>]. The original form of Miner's hypothesis was formulated to describe energy. Linear hypotheses assume that, in the case of a constantamplitude load, each load cycle, regardless of the phase of the fatigue process, contributes equally to the damage. This is similar for loads with variable amplitudes. Damage is a function of the number of cycles. The Palmgren–Miner hypothesis assumes that, for a multistage load program, a fracture occurs if the following condition is met.

$$\sum \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_3}{N_2} + \frac{n_3}{N_3} + \dots + \frac{n_n}{N_n} \le D_L$$
(2)

The total value of the damage must meet the condition  $D_L$ . Due to the presented method, it is possible to enter real data that allow for the correct evaluation of the structure in the case of its fatigue strength. To give an example, the results of the fatigue analysis of welds, prepared according to the data obtained from measurements for one year of machine operation are presented. The following operating conditions were determined to constitute a typical cycle:

- ✓ Machine usage in 1 year − 120 days;
- ✓ Working time in one working day -6 hours;
- Three working cycles forging walls, ceilings and floors;
- The ratio of working cycles: walls demolition 50% of the annual use of the machine, ceilings demolition - 25% of the annual use of the machine, floors demolition -25% of the annual use of the machine.

For the assumed parameters, the ranges of principal stress

changes were calculated, and then for a given number of cycles for each case during the machine's operation, the partial fractions of Equation (2) were calculated to assume the fatigue strength according to the Palmgren-Miner hypothesis. All partial fractions corresponding to the cycles in each machine configuration were summed up and the results are presented as the value of the destruction parameter. For a better illustration of the levels of this coefficient throughout the structure, the results are presented as contours lines. In this case, it should be noted that the analysis of the structure takes place only in the vicinity of the welded joints. Since there are different positions of the arms of the machine in the calculations, it is difficult to perform operations to determine the range of stress changes. Using Python scripting in Abaqus CAE it is possible to work on the results obtained regardless of the positions of the arms in different simulations, using the number of nodes in the model [38]. The destruction parameter calculated using nodal values for all analyzed cases is presented on one of the selected configurations. For the assumed cycle, the results are presented for one year of machine operation. These results are shown in Fig. 21.



Fig. 21. Destruction parameter presented as contours for the assumed working cycle of the machine in one year: (a) Whole machine; (b) Arm 1; (c) Arm 2; (d) Arm 3.

This analysis completes the entire process of the presented method and allows for further work in the event of failure to meet the conditions set by the constructors or ends the work by confirming the correctness of the assumptions made.

# 4. Discussion

Currently, numerical and experimental methods are already employed for assessing the fatigue of structures or validating construction assumptions. However, these methods typically focus on specific machines, predominantly excavators, and may not be directly applicable to demolition robots due to their unique characteristics. The configuration of robotic arms, distinct forces acting on the structure, and varied work cycles necessitate a tailored approach.

The main problem in assessing the fatigue life of this type of machine structure already at the design stage is lack of knowledge of the machine's load cycles and the exact magnitude of the forces exerting it. The use of only the numerical method or only measurements on a real object is insufficient in this case. The problem was faced and a method was proposed, which allows addressing the issue in future designs of this type of machine, in assessing their fatigue strength and, above all, the fatigue strength of welds, which are the critical and least durable part of the structure. The presented method gives an indication of the direction in which solutions should be sought for machines for which precise design guidelines have not been created, and also to prevent their uncontrolled damage in the future. The use of resistance strain gauges allows not only to determine the actual effort of the machine, but also to determine the number of cycles under a given load, as well as to determine the ranges of load changes during operation. This is the knowledge necessary to correct construction assumptions already at the design stage. The method presented shows how to determine the measuring points on the machine. When the measurement points are correctly located, errors related to the subsequent reading of the actual loads acting on the machine during operation can be avoided at an early stage.

Demolition robots have recently become machines that are often used in demolition work, due to the improvement of the operator's work safety, who no longer must be in the work environment, due to the possibility of remote control. Due to their use, there have been no guidelines on how to design this type of structure, e.g. considering the impact of a dynamic hydraulic hammer. There is a lack of guidelines and standards that would allow designers to clearly establish boundary conditions during design.

The presented method integrates numerical simulations (FEM) with real measurement data obtained during machine operation, allowing for a more accurate and reliable assessment of fatigue strength. The use of real measurement data enables verification and correction of numerical models at an early stage of design, minimizing the risk of unforeseen damage. Precise determination of the placement of strain gauges enables effective data collection, crucial for fatigue strength assessment. The method also reduces the number of required simulations by efficiently utilising data from a single model for multiple operational scenarios of the machine, thereby reducing time and research costs. Through precise modelling and testing, the method contributes to increasing the safety of demolition operations by preventing failures and uncontrolled machine damage. Additionally, it enables a more comprehensive understanding of the loads acting on the machine in various operating configurations, which is crucial for assessing the fatigue of machines subjected to variable cyclic loads. These advantages make the proposed method a valuable improvement over traditional approaches, focusing on a more holistic and precise approach to the design and assessment of demolition machines. In both qualitative and quantitative approaches, the method exhibits a significant advantage over classical methods by not omitting cases of intermediate positions of the links in space. This enables a more precise determination of coefficients responsible for fatigue strength, such as those related to welds. In the case of the classical approach, only one maximum and one minimum position of the arms system would be considered, whereas in the presented method, this has been expanded. The choice of the number of cases depends, of course, on the complexity of the problem. However, a greater number of cases in both quantitative and qualitative assessment allows for a more precise evaluation of the structure.

The presented method allows for the analysis of this type of machine and, in the future, may allow for the development of design. The presented method is a developmental method, i.e. it can be easily extended or changed to meet the needs of other users. Ongoing research is focused on enhancing the presented method to incorporate a broader array of operational variables, including precise positioning of machine arms, and to minimize the requisite number of strain gauge points.

# 5. Conclusions

The article presents a method for estimating the fatigue of remotely controlled machines for demolition works. Due to the lack of guidelines for the design of this type of machines, especially in terms of determining the forces acting on the machine during operation and precise determination of load cycles, the presented method solves this problem. The use of measurements of the machine load value during operation allows determining not only the actual forces acting during operation, but also the load cycles with which these forces occur. This allows for precise determination of the input data for the fatigue analysis of the structure. Lack of this information results in errors in the design assumptions themselves and thus can lead to uncontrolled damage to the machine. The described method eliminates errors already in the initial assumptions, which improves work safety and prevents uncontrolled damage to the machine. The presented method of numerical and experimental comparison will allow, in the future, to develop standardised guidelines, which are not defined now, for a more reliable and correct design of this type of machines.

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