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INVESTIGATION OF STRENGTH AND CALCULATION OF WEAR RESISTANCE OF A QUICK-RELEASE MECHANISM IN CONNECTION WITH THE WORKING ATTACHMENT OF A HYDRAULIC EXCAVATOR

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Abstract. In this study, a model of a quick-coupler device is investigated and presented within simulation modeling software. A method is presented that enables the design and construction of a simulation model of a quick-release device as an alternative to physical modeling for further investigation. The predicted service life of the tested quick-coupler model is estimated based on the S-N curve (fatigue curve). The S-N curve illustrates the relationship between stress amplitude and the number of cycles to material failure.

Keywords: Quick-coupler mechanism, quick-coupler, model, excavator, attachment, boom.

1 Introduction

The construction and development of roads involve a series of diverse and sequential operations that require specialized work equipment. Leading manufacturers of road construction machinery aim to expand the range of work attachments that can be used with base machines. To achieve these goals, quick-release couplings are widely utilized, enabling operators to change work tools quickly and conveniently**.** [1]

A quick-release coupling system may face limitations in compatibility with existing tools or attachments. Equipment not specifically adapted to a particular system may prove incompatible or require additional modifications, reducing its versatility and ease of operation. Furthermore, the presence of numerous moving parts and complex mechanisms increases the risk of breakdowns and malfunctions, necessitating regular maintenance and inspections to ensure the system's operational reliability. [2]

It is essential to focus on simplifying the design of quick-release couplings while maintaining their functionality and efficiency. Reducing the complexity of the design will lower production and maintenance costs, potentially leading to significant savings. Another key aspect is ensuring the system's compatibility with existing tools and attachments. This can be achieved by developing the system in accordance with widely accepted standards or by incorporating adapters that enable compatibility with various types of equipment. [3]

To evaluate the designs of quick-release couplings and identify potential functional limitations, it is recommended to create a physical model. However, it should be noted that such a process is costly and resource-intensive. Fortunately, modern digital technologies and software can be utilized to perform computer simulations, establishing functional parameters

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that closely approximate real-world conditions. These tools also enable the assessment of designs under high loads and varying conditions. [4]

For the calculations of the model, the SolidWorks Simulation software was used, as the displacements of the structure under the applied load were small, and the stresses within the structure did not exceed the elastic limit. This allowed the calculations to be performed within the assumptions of linear analysis. However, if the stress exceeds the elastic limit and the displacements are sufficiently large—large enough to cause the load direction to change—then a nonlinear analysis must be conducted. In such cases, the load is applied incrementally in steps, and at each step, the stiffness matrix of the structure is recalculated, and the direction of the loads is updated.

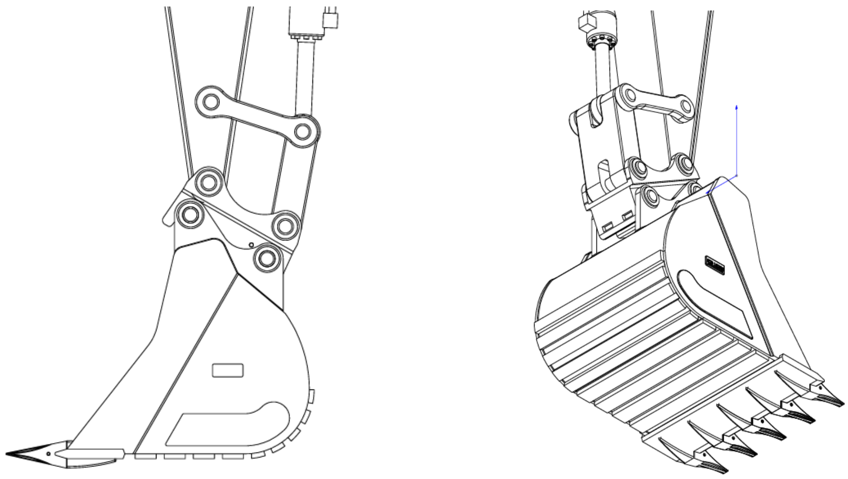

Fig.1 Demonstration of the QCM attachment with the bucket.

In the computer simulation, the geometric parameters of the quick-release coupling were used (Patent No. 9769 for the utility model "Mechanical Quick-Change Device for an Excavator," 2024/1097.2 dated September 10, 2024). Modern digital technologies, such as the SolidWorks Simulation software, enable computer modeling and the establishment of functional parameters that closely approximate real-world conditions. Additionally, the design can be evaluated under high loads and various unlikely scenarios.

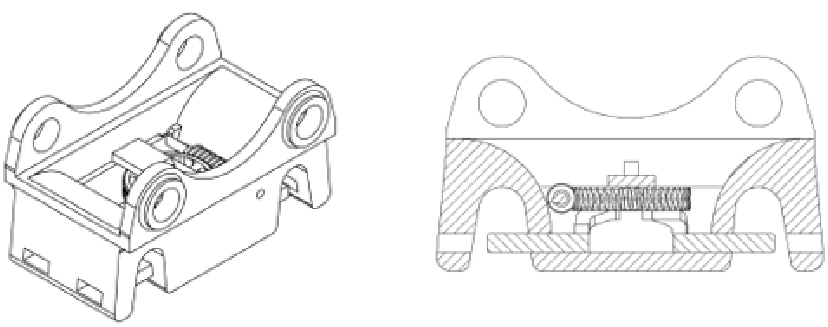

Fig. 2. Model of the quick-coupler mechanism

The quick-release mechanism for attaching and detaching various excavator attachments is characterized by a robust one-piece body equipped with docking holes, an internal rib supporting a removable beam, on which a worm drive is mounted. The worm drive is powered by a gerotor hydraulic motor. A wide gear wheel is connected to two sturdy rectangular bolts via two curved connecting rods, which move synchronously in opposite directions and engage with rectangular slots in the dense walls. The mechanism also includes holes designed for auxiliary or emergency assistance in unlocking the system using a universal socket wrench of standard sizes 17x19x21x1/2" DR, 380 mm. [5] (Fig. 1, 2).

2 Statistical Analysis of the QCM Model in the "Arm-QCM-Bucket" Assembly

This research involves adapting the standard method of multi-stage modeling of dynamic loads to the "Arm -- QCM -- Working Tool/Bucket" system. This approach allows for the creation of a variable-based model that considers various factors, including operating conditions, the type of soil or material being processed, the duration of the task, the equipment's service life, and the type of technological operation. Considering these factors, a comprehensive model of the base machine's operation can be developed.

The goal of the research is to create a working tool or attachment that meets strength and stiffness criteria, is reliable in use, durable, and has lower metal consumption and superior technical characteristics compared to previous designs.

At the initial design stage, the primary configuration of the element and its attachment methods to the equipment components are determined. Approximate preliminary values of dimensions and cross-sectional shape are determined based on operating conditions, external loads, the technological process, and the labor intensity of the element as part of the equipment. In the second design stage, the element's bending mode is evaluated, and its strength parameters are determined with adjustments to its shape and dimensions. The level of accuracy achieved in approximating the actual strength and creating a rational design largely depends on the choice of the correct calculation method.

The first goal is to select the most functional equipment components, ignoring non-functional (structural) elements, and to idealize the design and its attachment to the equipment parts.

The evaluation of computational models is conducted using standard structural design methods, which allow for the assessment of statistically indeterminate forms of frame structures, determination of stresses and displacements at predefined points in the structure, and identification of patterns in the computational model that correspond to the actual structure. The machines are designed for the range of elastic deformations of metal, and the structural elements are assumed to be linear solid bodies. Statically determinate systems have a maximum of three links (derived from the number of basic static equations of planar systems). Systems with more than three links are statically indeterminate, including systems with closed loops, where stresses in the elements cannot be calculated using static equations. The number of redundant links *N*, which determines the degree of static indeterminacy of a system consisting of B elements, is calculated by formula (1).

$$N = 2Sh + C_0 - 3B \tag{1}$$

where $2Sh + C_0$ is the number of links in the system,

$3B$ – the number of necessary links.

The system, including "Arm - QCM - Working Tool," is statically indeterminate, meaning that the presence of redundant links in the system hinders the free movement of nodes. To calculate the displacement at a specific point in the system caused by an applied load, the Mohr formula is typically used, which is derived from Betti's reciprocal theorem and Hooke's law.

The process of determining displacement involves creating a diagram of internal forces (moment M_c, normal forces N_c and lateral (shear) forces Q_c) based on the load P_i = 1, assuming a fictitious state of the system where a unit moment $M_i = 1$ is applied in the direction of the desired displacement, constructing diagrams M_i , N_i, Q_i , reflecting the action of unit forces. Finally, using the Mohr formula to calculate the desired displacement:

$$\Delta_i = \sum \int_0^s \frac{M_i M_p ds}{EJ} + \sum \int_0^s \frac{N_i N_p ds}{EF} + \sum \int_0^s \frac{k Q_i Q_p ds}{GF} \quad (2)$$

In statically indeterminate systems, the forces in the elements are influenced by numerous factors, such as loads, temperature changes, support displacements, assembly defects, geometric dimensions of the structure and its cross-sections, and the physical properties of structural materials. There are two main methods for designing such systems: the force method and the deformation method (also known as the displacement method).

Once the internal forces are obtained, the next step is to determine the stress values acting in the most critical cross-sections of the structure. The corresponding formulas for determining material strength are used to obtain stress values. These calculated stress values are then compared with the allowable stress values, which are obtained by dividing the critical stress of the material $[\sigma]$ by the safety factor *n*. For construction and road-building machinery, the critical stress is usually the yield strengthσ_τ, calculated for the elastic zone. The allowable stresses are checked using the formulas:

$$\sigma \leq [\sigma]; \ \ \tau \leq [\tau] \quad (3)$$

where σ, τ – calculated normal and shear stresses,

$[\sigma]$, $[\tau]$ – allowable normal and shear stresses under static load.

The use of interchangeable working tools in computer simulations of the "Arm - QCM - Working Tool" system can help evaluate and compare the impact of dynamic loads on the quick coupling device. When designing a new model, these evaluations can provide initial technical parameters, such as weight *m*, load capacity *P*, and bucket capacity *q*, based on the operating conditions specified in the design brief.

Accurate determination of loads on the excavator's working equipment and the determination of safety factors are crucial for the operational capabilities, reliability, weight, and energy consumption of the structure.

As is known, single-bucket excavators are dynamic machines, and most of the energy consumption, about 70%, is spent on lifting the boom and arm, while the remaining 30% is used for lifting and moving the working equipment. The bucket may encounter an insurmountable obstacle in various positions, which can change the balance of forces, their direction, and magnitude. However, selecting calculation schemes and load combinations for strength calculations with greater accuracy can be challenging due to several factors.

These factors include the dependence of stresses on external forces, positional relationships between elements, the main external load being the resistance to the displacement of the cutting edge, and the fact that maximum stresses in different elements do not occur simultaneously. Additionally, working attachments and loads can be in thousands of positions, making it difficult to accurately determine stresses. [6]

Figure 3 shows the process of determining deformation, stress, and displacement when the boom is in its lowest position, the bucket is turned outward, and the digging force is directed against an insurmountable obstacle. In this position, no factors limit the digging force on the bucket's cutting edge.

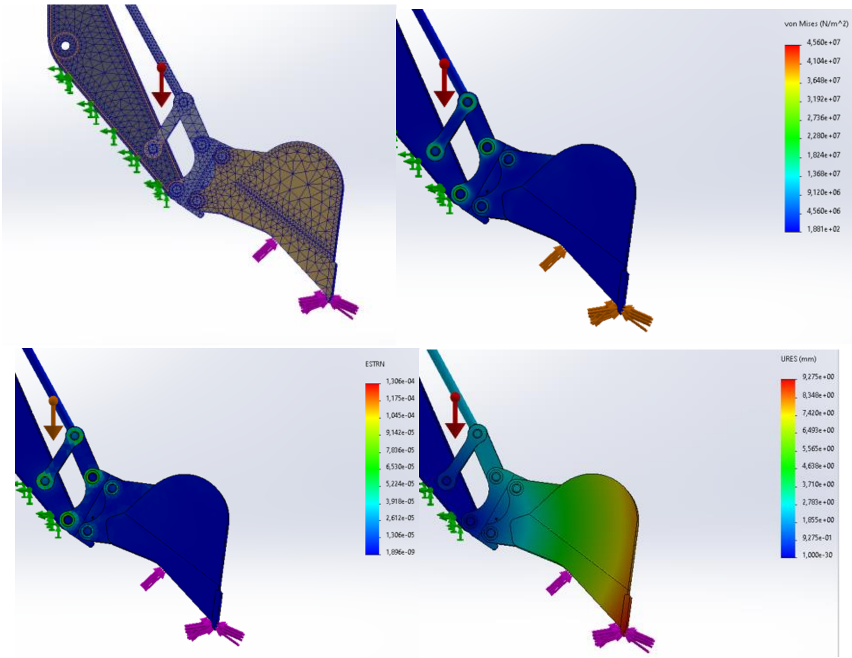

Fig. 3. Determination of static displacement in the "arm - QCM - bucket" assembly: a) mesh created with tetrahedral elements; b) static deformation; c) static stress; d) static displacement.

3 Calculation of the Stress-Strain State of the Quick Coupling Body

Calculations were performed for the quick coupling to determine its ability to withstand vertical loads. These loads were calculated based on the weight of the bucket when filled with soil to volumes of 0,65 m^3, 0,77 m^3 and 1 m^3. The forces were applied to the pins that attach the bucket, as shown in Figure 4. [7]

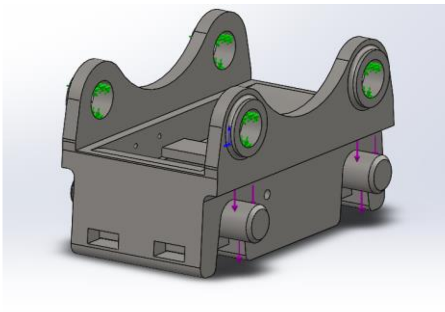

Fig. 4 Load application points

It was determined that the load on the bucket with a volume of 0.65 m^3 is 1.17 tons, while for the bucket with a volume of 0.77 m^3 it was 1.38 tons, and for the bucket with a volume of 1 m^3 - 1.8 tons. The quick coupling body is made of steel 09G2S (Fig 4), and Figure 5 shows the points where the loads are localized and applied to the quick coupling body.

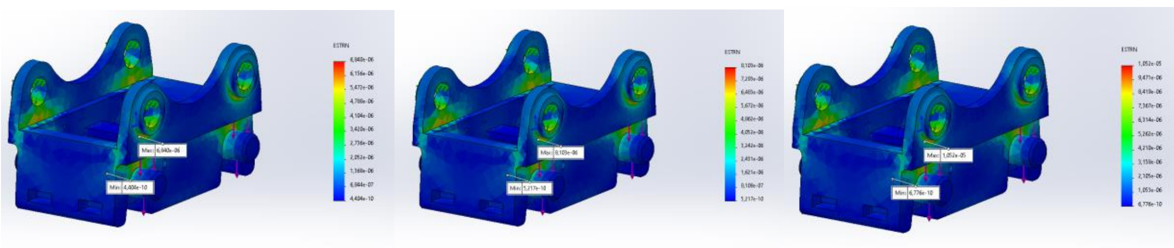

Fig. 5 Diagrams of loads acting on the QCM

The simulated coupling device was used to calculate the equivalent deformation, stress, and displacement. Table 1 shows the deformation and stress maps for the quick coupling after fatigue stress testing under operational loads.

Table 1 Determination of maximum displacement during operation with different bucket volumes

	a	b	c
Bucket volume, m^3	0,65	0,77	1
Load, tons	1,17	1,38	1,8
Maximum displacement (deformation), nm	69,4	81	100

The bucket with a volume of 1 m^3 provides the highest deformation value of 100 nm, while the lowest deformation value of about 70 nm is observed when using a bucket with a volume of 0.65 m^3. Similar calculations were performed to determine the stresses and displacements within the quick coupling body for different bucket volumes.

CONCLUSION

In conclusion, the computer model developed for the quick coupling mechanism and the structural calculations performed provide a cost-effective method for measuring the effective parameters of the machine when introducing additional elements to expand the machine's functionality and increase the range of working attachments. This, in turn, helps solve the problem of comprehensive mechanization of construction work based on the principle of a "single fleet."

Based on the calculations performed, it can be concluded that all parameters remain within acceptable limits, and the quick coupling system can withstand the loads specified by the manufacturer for this type of bucket. An algorithm has been developed and applied for modeling the prototype of the quick coupling as an element of the excavator's working attachment in the "arm -- QCM -- working tool (bucket)" system.

As is known, the traditional method of estimating fatigue constants uses a single set of experimental data obtained during uniaxial fatigue tests with controlled deformation. However, these constants do not provide compatibility conditions. The new 3D method presented in the article [8] preserves the mathematical and physical dependencies between the curves under consideration. Thereby providing comparable statistical values, just like the usual method, for both types of load. In some cases, the approximation quality, measured by statistical values, is more successful for the three-dimensional method. In the article by Hanuma, T., Pankaj, P., Biswas, P., Deepati, A., Benjeer, I., Kumar, A., "Friction Stir Welding Tool Life Assessment Through Fatigue Analysis". *Journal of Mechanical Engineering*, 2023 [9], the Miner's equation is presented, which is used to calculate cyclic durability, which in turn is very important for assessing damage accumulation.

The predicted service life of the QCM model, based on the S-N curve (fatigue curve) (Fig.6), depends on the level of applied alternating stress and the number of loading cycles. The S-N curve shows the relationship between stress amplitude and the number of cycles to material failure.

From the provided data:

At an alternating stress of approximately

4.03×1084.03×108 N/m² (point 680468)

the material can withstand approximately 1.00×1051.00×105 cycles before failure.

To predict the service life, it is necessary to know:

1. **Stress level**: What stress will be applied to the material under real conditions.
2. **Loading frequency**: How many loading cycles occur per unit of time (e.g., per day, month, year).

As an example, if the material is subjected to 1.00×1051.00×105 cycles per year at a stress of 4.03×1084.03×108 N/m², the predicted service life will be about 1 year before failure (without considering real operating conditions, including possible changes in stress and loading frequency).

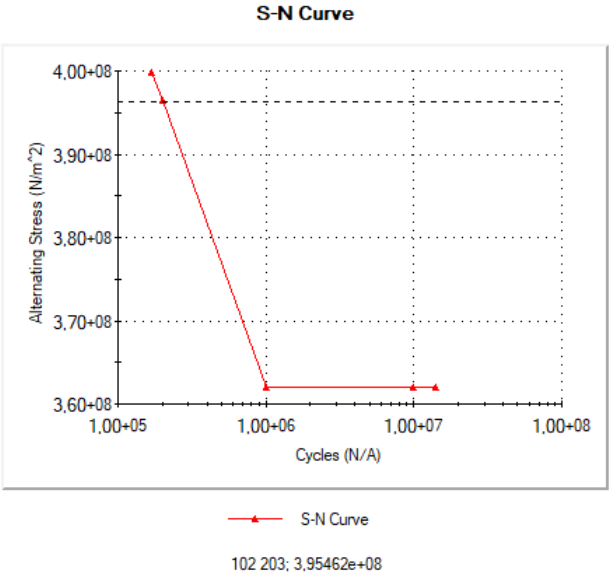

Fig.6 Fatigue curve of the QCM

The creation of a simulation model allows for the evaluation and comparison of loads acting on the quick coupling device while reducing material and labor costs associated with experimental research.

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