Numerical simulation of crack propagation in clinch joints

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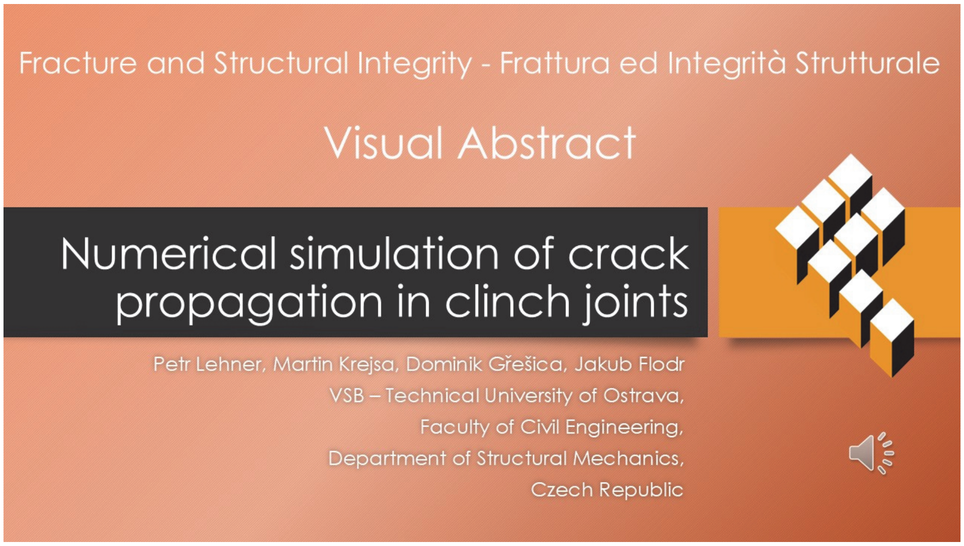

Fracture and Structural Integrity - Frattura ed Integrità Strutturale

Visual Abstract

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INTRODUCTION

The construction industry, as a fundamental branch of engineering, is currently undergoing significant transformations. These shifts are driven by advancements in construction technologies, the modernization and optimization of production workflows, as well as by evolving conditions in the labor market.

Currently, there is great pressure in many aspects to increase work efficiency. With regard to the often-great shortage of qualified workers, it is necessary to either partially or fully automate production processes [7]. In the production of structures themselves, there is already a gradual shift from manual production operations to semi-automated and later to fully automated production processes. This transformation is certainly demanding, but in its essence, it should lead to more reliable building structures and the quality of the implemented structures should increase in all aspects. Steel structures offer great potential for increasing efficiency in all aspects, and thin-walled cold-rolled sections can also offer much in this regard [4]. These are widely used as primary structural elements of small steel halls and buildings, civic buildings and similar smaller structures, which are completely made of thin-walled cold-formed sections. Another use can be found in large steel halls, but also in large objects in the form of cladding and secondary elements ensuring the load-bearing function for the cladding, which is often a technically unique solution adapted to size. In the field of connecting thin-walled steel structures, standard methods such as bolting joints [20] and welding [25] have been used for a long time and historically. However, robotization and efforts to save material are leading to the search for new alternatives. The clinch joint (see Fig. 1) is a promising alternative to the standard joining methods of thin-walled sheets and profiles used in the construction industry [5,11]. It is a mechanical connection by extrusion that uses only the material of the parts to be joined and does not add any additional connection. Clinching as such has long been used in many industries, most commonly in the automotive sector [16]. The reasons for this are speed when using automation, cost savings and high quality of the connection. Exactly these advantages need to be transferred to the construction industry and applied appropriately to the use of load-bearing structures. In this context, mechanical joining techniques such as clinching are gaining attention as potential alternatives to traditional methods. Clinching eliminates the need for additional fasteners or thermal input, which may be advantageous in lightweight, prefabricated construction systems. Although this technique has been extensively applied in automotive and electronics industries, its implementation in civil engineering remains limited, primarily due to the lack of design standards and insufficient understanding of failure mechanisms under complex loading scenarios.

The disadvantages are the fragility of the connection itself and the lack of information on the behavior of such a connection under, for example, cyclic or extreme stresses. It is the cyclic stresses induced by environmental influences that can be critical in the loading of building load-bearing structures and can induce failures in the connection - i.e. cracks - leading to destruction [18,21]. The principle of crack initiation and propagation in a clinch joint is like that of other steelwork details or connections [19]. In a clinch joint, plastic deformation is produced under load and is related to local stress. Unlike other connections, there is an additional imposed stress during the clinch joining process itself that affects the resulting behavior. Stress characterization in clinch joints is a complex problem that involves the determination of both normal and shear stresses. In the initial phase, small cracks develop in the joint area, especially in places of stress concentration (e.g. in the so-called neck). These cracks are initiated by repeated loading and their propagation is slow. During subsequent plastic deformation due to stress concentration, the material is weakened. The resulting crack propagates in the base material and gradually weakens the entire joint. When a critical size is reached, the neck of the clinch joint fails and thus the two joined sheets separate. Since crack initiation is influenced by factors such as material properties, joint geometry, bonding parameters, and possibly imperfections on the surface, it is necessary to combine a research process involving experimental and numerical investigation of the entire process [14,23,25].

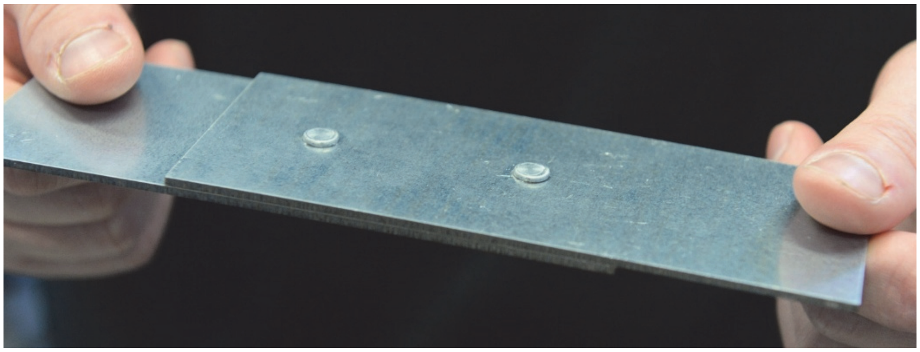


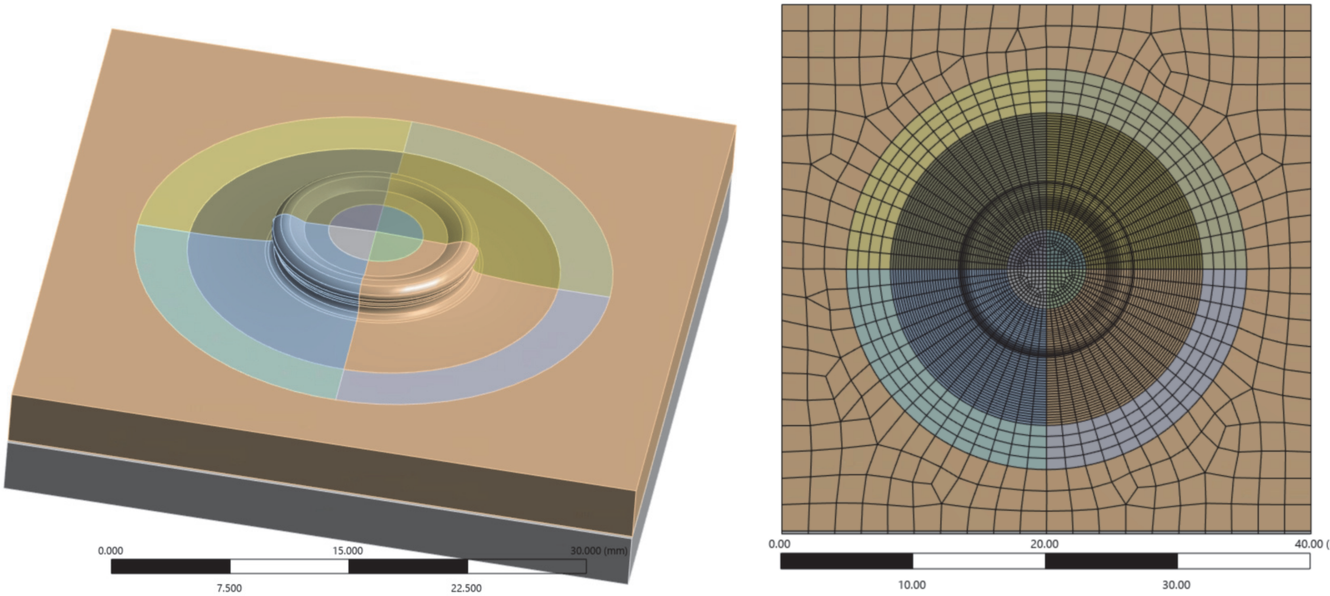
Figure 1: Example of joined sheets using clinch technology.

Nowadays, the finite element method (FEM), implemented for example by Ansys software [2], is a very suitable and useful tool for numerical analysis. With this software it is possible to simulate the exact geometry of the joint and all boundary conditions. It is always necessary to use as realistic a material description as possible and to apply a suitable finite element size. For numerical analysis related to crack initiation and propagation, the process can be divided into several steps. The first important step is the static analysis, in which critical stress can be evaluated to determine the crack initiation sites. Next, the crack propagation needs to be determined, and several techniques can be used for this, such as the Virtual Crack Propagation Method [12] or the eXtended Finite Element Method (XFEM) [24]. In addition, a fatigue analysis is also suitable to simulate cyclic loading and predict the service life of the connection with respect to the risk of fatigue fracture [13,17]. XFEM adds so-called enrichment functions to the classical FEM. These functions are added to the classical shape functions inside the elements that contain discontinuities. Enrichment functions capture the singularity and allow modeling of discontinuities without the need to split the mesh. The mesh generated for XFEM can generally be coarser and independent of the geometry of the discontinuity. This significantly simplifies the modeling and allows easier modeling of dynamic crack propagation, since it is not necessary to constantly reorganize the mesh. It should be noted that in this article the results of

the classical FEM analysis are presented, which was time-consuming, but it was sufficient for the basic description of the problem, since XFEM requires more advanced programming skills.
In this paper, the numerical analysis is simply described and applied to a typed clinch connection of two plates suitable to produce thin-walled sections of load-bearing structures. Boundary conditions and assumptions for the calculation are given in the next chapter.

NUMERICAL MODELS AND BOUNDARY CONDITIONS

The data presented here focuses on a narrow part of the research on clinch joint uses in the construction industry. Initial results of static numerical analysis and experimental investigation have already been published [8,10]. However, no relevant calculations related to fatigue of clinch joints have been performed to date. Fig. 2 shows a view of the prepared numerical model with separate parts.



(a) (b)

Figure 2: Numerical model of the clinch joint: (a) axonometry, (b) plan view of FEM mesh.

Numerical and material model

For this task, the most realistic numerical model was created in Ansys [3]. The geometry is based on previously created and experimentally tested samples. It is a connection of two sheets with a thickness of 2.67 mm, which was previously analyzed statically [10]. The numerical model was based on a so-called geometric and material nonlinear analysis (GMNA), containing 378,600 SOLID186 elements and 882,339 finite element network nodes. The SOLID186 element is suitable for the numerical model of clinch joints because, as a 3D quadratic element, it accurately captures nonlinear deformations and contacts in the area of plastic joining of sheet metal. GMNA allows for more accurate modeling in terms of taking into account large deformations, nonlinear material behavior. The use of GMNA allowed the incorporation of both large displacements and plastic strain behavior, crucial for replicating the real deformation around the neck of the joint. GMNA was selected over linear analysis methods because it captures post-buckling effects and residual stresses more accurately, which are dominant in clinch joints under cyclic loading. This brings realistic results, more accurate stress distribution, and the possibility of combining with other types of analysis. For the case of a clinched joint of thin-walled sheets, it is therefore an ideal choice [22]. The use of a different size of the finite element mesh was prepared based on a sensitivity analysis including the behavior of the simplified model and boundary conditions. Although the present model is based on previously verified geometries [10], future work should incorporate full experimental validation of the fatigue behavior, including the measurement of crack initiation and growth rates. This step is crucial to ensure that the numerical predictions align with the real-world response of the joint under cyclic loading. Fig. 3 shows the finite element mesh where the different settings for each part can be clearly seen. For parts that are directly part of the clinch connection the mesh is fine, while for less important parts the mesh is coarser to save computational time.

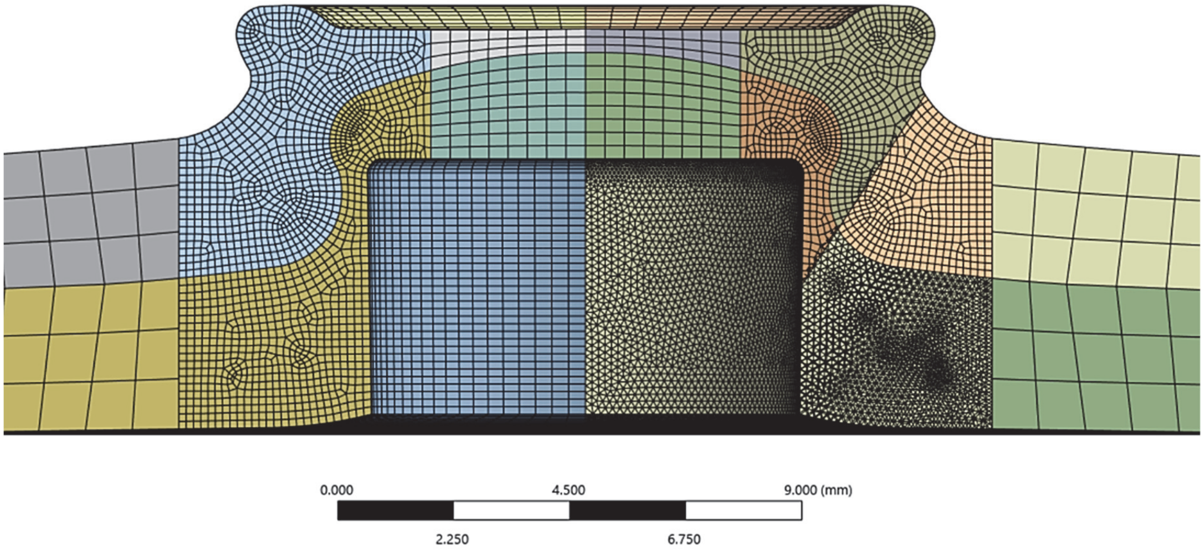


Figure 3: Longitudinal section through the model at the center of gravity.

The material model was multilinear with isotropic hardening (see Fig. 4), whose parameters were obtained from tensile tests and inverse numerical analysis of tensile test [9].

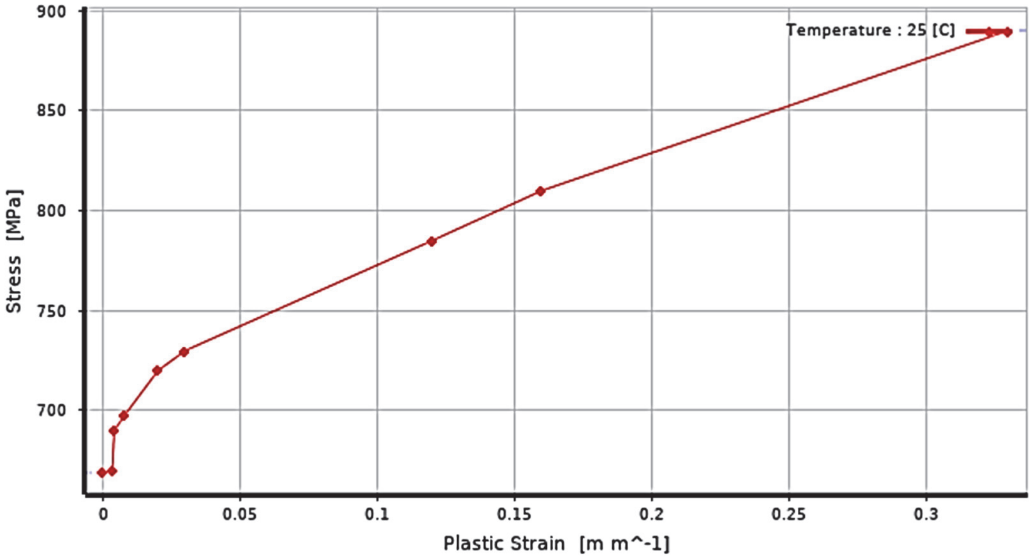


Figure 4: Stress-strain diagram (material model).

Simplified fatigue analysis

One of the presented procedures and results is a simplified fatigue analysis. Basically, the aim here is to evaluate the critical fatigue points on the clinch joint. The load force is determined based on the first shear test condition. It should be noted that the magnitude of stress does not play a role in this analysis. Cyclic loading is then used to estimate the service life. The critical stresses on the elements are confronted with the S-N curve of S235 steel (see Fig. 5). This curve is obtained from EN 1993-1-9 [1]. The higher value of stress, the fewer cycles the element or part of the structure can withstand, on the contrary, at lower value of stress the number of cycles is higher. By using the FEM network and the results, it is possible to obtain value, i.e. the number of cycles after which a crack can occur - this is referred to as life analysis. Similar analyses are known in the literature [6], but have not yet been applied to clinch joints.

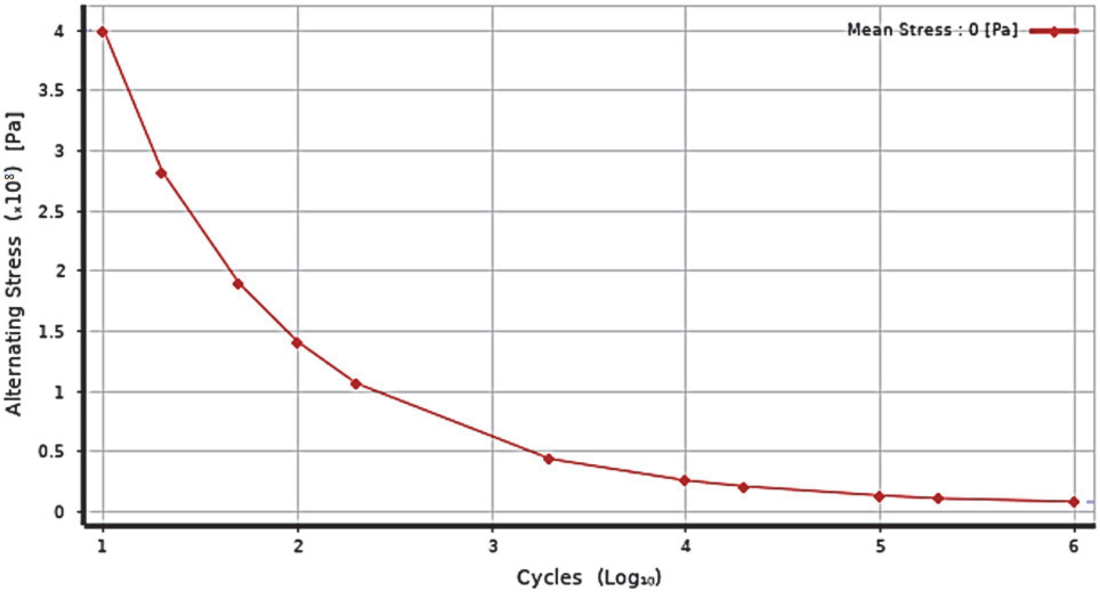


Figure 5: S-N curve of steel S235.

Crack parameters

One of the important parameters is the so-called stress intensity factor *K*. This parameter depends on the stress in the specimen at a sufficient distance from the crack, the shape of the crack and the method of stressing. The parameter can be determined by numerical calculation. Due to the simplifying boundary conditions, an assumed initiation crack was introduced, which is at the neck of the clinch joint. This place is most stressed, and there is the smallest number of cycles in the life analysis. Therefore, in the framework of the presented geometry, the assumed crack was applied (see detail of mesh in Fig. 6) and the parameters *K* were determined for all three modes of crack growth: Mode I - tensile load perpendicular to the crack plane, shear load in the crack plane and Mode III - shear load perpendicular to the crack plane [15]. As a result, it could be determined which Mode would be the most critical for the uplifted geometry of the clinch joint. Furthermore, it was possible to determine a range of stress intensity factor ΔK for all three modes that could be used to estimate the rate of crack propagation in the joint.

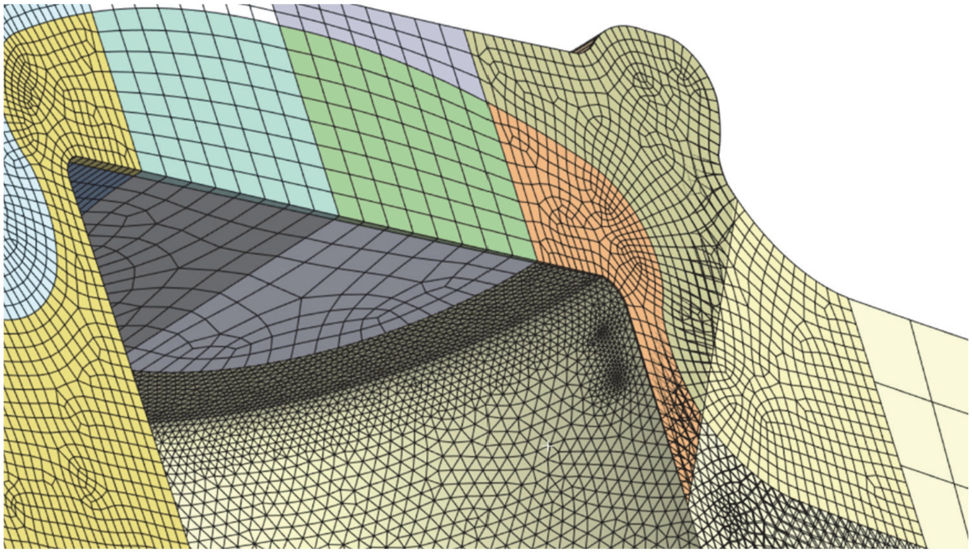


Figure 6: Detail of the mesh around the crack.

RESULTS

Simplified fatigue analysis

The first phase of the numerical analysis focused on identifying critical points using a simplified life cycle analysis. The graphical output shown in Fig. 7 illustrates the number of loading cycles in each finite element of the numerical model. The critical point reaches 62 cycles. This means that this is the point where damage due to cyclic loading begins first. This low number of cycles indicates a region of high concentration, making it the most vulnerable zone to fatigue failure. It is also clear that a relatively large portion of the inner neck of the joint is within the 500-cycle range. This indicates that there is significant stress in this region and a potential risk of failure. This region, which experiences a moderate number of cycles, indicates a less severe but still concerning level of stress that could contribute to the initiation and propagation of fatigue cracks over time. Regions with cycle numbers in the thousands indicate a robust structure capable of withstanding repeated loading without significant degradation. Finally, the load is relatively low in other areas, which is reflected in the high cycle values. In other words, in these areas the material can withstand a large number of cycles without failure. The distribution of these cycle numbers in the model provides the basic information for the second part of the numerical analysis.

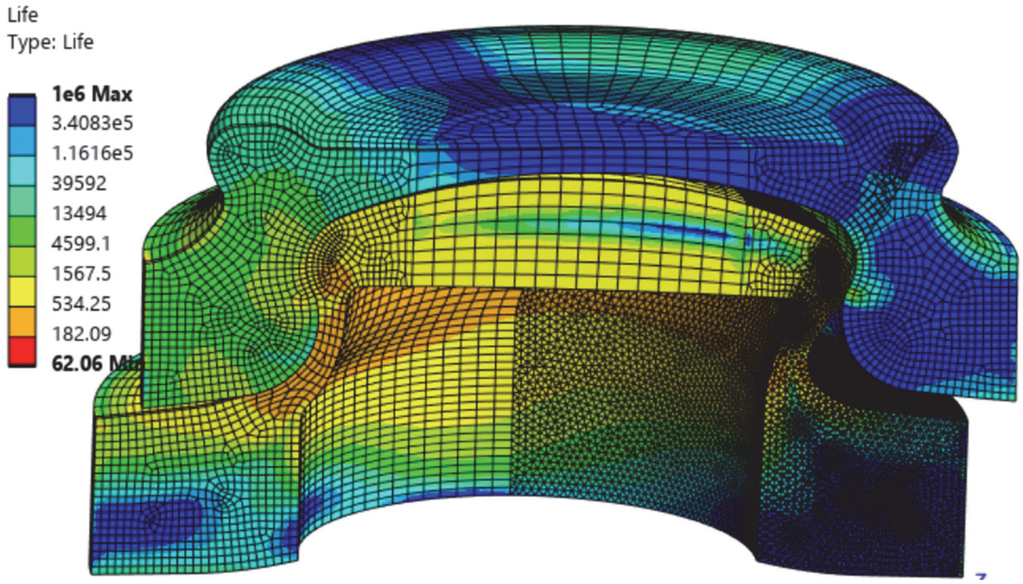


Figure 7: Visualization of results of stress life cycle analysis.

Crack initiation parameters

Based on the assumptions and service life analysis performed above, it appears that the neck area of the lower part of the joint is a critical point in terms of failure. Crack initiation is expected here, and therefore a crack initiation analysis was performed in this area. The result of this analysis is the determination of the stress intensity factor *K* and the range of the stress intensity factor *⊿K*. The range *⊿K* is calculated as the mean difference between the maximum and minimum values of the stress intensity factor, which allows us to better understand the dynamics of crack propagation due to cyclic loading. It is important to note that this is not a pure difference between the minimum and maximum, but an interpolation value. The detailed results of the numerical analysis, including the *K* and *⊿K* values, are presented in Tab. 1. This table provides a quantitative overview of the behavior of the material in this critical area and serves as a basis for further evaluation of the service life and optimization of the design.

Modes of crack growth	Min *K* [MPa/mm]	Max *K* [MPa/mm]	Mean *K* [MPa/mm]	*⊿K* [MPa/mm]
Mode I	-3337.1	1591.1	57.2	1234.4
Mode II	-1223.8	1823.4	53.9	875.9
Mode III	-1293.3	541.9	-287.5	328.0

Table 1: Stress intensity factors.

By evaluating the three stress intensity factors modes, it is possible to determine which is the worst for a given shape and boundary conditions. By simply comparing the parameter ΔK, we can state that the most critical is Mode I, i.e. the so-called crack opening, followed by Mode II, i.e. shearing, and the smallest value of the parameter is Mode III, i.e. tearing. The results also show negative values for all modes, which show that the compressive stress at the crack tip is as expected, considering the way the neck shapes change. Such negative K-values are a direct result of local compressive fields around the neck caused by the clinching process itself and are supported by residual stress measurements. These results suggest that crack closure may be present in early loading phases, potentially delaying initiation.

CONCLUSIONS

This study focuses on numerical modelling of crack propagation in clinch joints. The finite element method (FEM) was used for a detailed analysis of the behaviour of these joints under load, and in particular to understand their fatigue behaviour and the mechanism of crack formation. The simulation made it possible to examine the complex interactions of forces and stresses in key areas of the joint. A simplified fatigue analysis performed as part of the study revealed critical stress concentration points where the probability of crack initiation is highest. This is the location of the neck. The results obtained made it possible to estimate the number of load cycles required for crack initiation, thus highlighting the vulnerability of the inner part of the joint neck. In addition, an analysis of stress intensity factors (K) was performed, which provided valuable information on the dynamics of crack propagation. This analysis made it possible to identify the dominant modes of crack growth, which is key to understanding and predicting the failure of clinch joints due to fatigue. Mode I was determined to be dominant, showing a 30% higher range of stress intensity factor than Mode II and a 75% higher value than Mode III. These values indicate that tensile opening is the prevailing mode of failure in the analyzed clinch joint geometry, which is consistent with the expected behavior of thin-walled connections subjected to in-plane tensile cyclic loads. Further parametric studies may reveal how geometric modifications (e.g., die shape or material thickness) influence the dominance of specific fracture modes. Further research must address the performance of extensive experimental tests to validate the numerical model and ensure its reliability for predicting the behaviour of clinched joints under real-world conditions. The experimental program is part of a large project that has recently begun. The scope of the program includes tests of raw materials, static tests of clinch joints, and fatigue tests of clinch joints. The article thus presents a clear direction for research in this area. It would also be valuable to extend the numerical models to account for more complex loading scenarios, such as combined shear and bending or temperature-induced stress variations. Furthermore, studying the influence of different die geometries and sheet material combinations on fatigue resistance could offer practical guidelines for the optimization of clinch joints in construction applications.

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