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Investigation of Double Notch Influence on Crack Propagation in S355 Steel: Experimental and Numerical Study

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Abstract. This paper presents a study aimed at establishing a numerical finite element model of the tensile behavior of an S355 steel under the effect of double notching using CAST3M software. This approach is of significant importance in the understanding and design of mechanical structures. The main aim is to provide an effective method for assessing stress concentration and crack propagation in such specimens, which could help improve the reliability and durability of mechanical components.
The results indicate that maximum stress is found at the bottom of the notch. The numerical study also shows that this maximum stress gradually decreases along the specimen axis up to 2 mm, and then stabilizes at the nominal stress value. Furthermore, the stress concentration factor increases proportionally with crack length and applied stress. These findings offer valuable insights into the understanding of material behavior in the presence of cracks and stresses, and may contribute to the development of more accurate design and evaluation methods for steel structures.

Keywords: Maximum stress, Numerical simulation, S355 steel, Stress concentration factor,

1 Introduction

S355 steel, widely used in various industrial applications, is subject to irreversible damage processes due to the presence of defects. The initial stage of crack initiation in this material accounts for a significant proportion of its service life [1-2], especially at low stresses. Industrial structures, on the other hand, inherently contain a variety of defects such as microcracks, inclusions and cavities, which can lead to crack initiation [3-5] and, consequently, to stress concentration-induced structural failure.
Faced with this challenge, it becomes crucial to characterize the harmfulness of these defects within structures, and ideally, to estimate the remaining service life of the installations concerned [6]. Various approaches have been explored for this purpose. Basic disciplines

such as fracture mechanics, fatigue and reliability of components and structures are mobilized [7-8], but they do not always offer simple analytical solutions for complex structures. Moreover, traditional experimental methods are costly and often complex to implement.
In the literature, various studies have been carried out to understand the impact of cracks and geometric defects on material behavior [9-13]. For example, researchers in [14-17], have numerically investigated the harmfulness of semi-elliptical cracks in cylindrical shells, studied stress distributions at the top of cracks originating from notches, or analyzed correction functions and J-integrals to assess the effects of defects on thickness transition.
It is well established that the J-integral plays a crucial role in elastoplastic fracture mechanics, characterizing crack initiation and propagation in ductile materials. The presence of a notch in a structure thus proves more dangerous than the simple mechanical reduction of the cross-section supporting the transmitted force [18]. The harmfulness of notches depends not only on their size, but also on their geometric parameters, such as the radius and angle of the notch [19].
To understand this phenomenon, the finite element method is an essential tool. It enables the behavior of complex structures to be studied in depth, and is an ideal way of solving the industrial challenges associated with crack propagation and stress concentration in materials. Our aim is to develop a numerical finite element model of a specific tensile specimen configuration featuring a double notch. This task will be carried out using CAST3M software; a tool specialized in the numerical simulation of complex mechanical behavior. The approach is of great importance in the field of structural engineering, as it enables mechanical structures to be analyzed and designed by simulating their response under different loading conditions. By focusing on this particular tensile specimen configuration with a double notch, our work aims to explore in depth the complex interactions between geometry, materials and stresses, thus offering valuable perspectives for structural optimization and mechanical failure prevention.
Note that, the use of a double notch configuration in this study brings a new perspective compared to the traditional single-notch specimens. By incorporating two notches, the specimen better simulates the complex stress distributions found in real-life engineering situations, where multiple defects often exist. This approach allows for a more accurate understanding of stress concentration and crack propagation, offering valuable insights into material behavior under realistic conditions. This work thus pushes the boundaries of traditional fracture mechanics, providing a more effective method for evaluating the durability and design of structural components

2 Experimental and numerical methodology

2.1 Material and experimental method

In our study, S355 steel was used, characterized by a Young's modulus of 200 GPa and a Poisson's ratio of 0.3, with a composition of 0.29% carbon, 1% manganese, 0.09% phosphorus, 0.05% sulfur, 0.20% silicon and 0.20% copper. The specimen preparation conditions used are:

- The machined cross-sectional area of these specimens measures 221.9 mm²;
- The V-shaped notch was machined using a roughing cutter (Fig.1), creating a flat-bottomed notch approximately 0.5 mm thick.
- The radius of the notch base was examined under a microscope at 280 magnification;
- The root of the notch is carefully finished with a sharp burr to match a 60° angle. The radius obtained is less than 0.1 mm.

– The cuts produced a radius of around 0.05 mm.

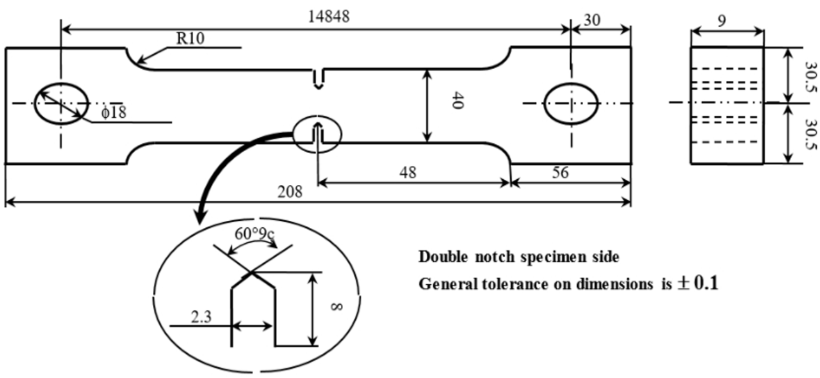

Fig. 1. Dimensions of the steel V-shaped specimen used.

The geometry of the specimen and the machining tolerances are essential factors in crack initiation, especially when it comes to the precision of the notches. In this study, the V-shaped notch was carefully machined using a roughing cutter to achieve a flat-bottomed notch around 0.5 mm thick. The radius at the base of the notch was examined under a microscope at 280x magnification, and the notch root was finished with a sharp burr to achieve a 60° angle. The resulting radius was less than 0.1 mm. These meticulous machining steps are critical in ensuring a consistent notch geometry, which is key to accurately evaluating crack initiation and stress concentration. Any variations in the specimen's geometry or machining tolerances could influence the stress distribution and crack initiation, potentially affecting the results. Therefore, it is important to pay close attention to machining tolerances to minimize the impact of any deviations and ensure the reliability of the experimental findings.

2.2 Numerical modeling

In this study, we examine a specimen with double lateral notches, subjected to tensile stress in Mode I, resulting in crack initiation. The specimen was modeled using the finite element method to assess its behavior. On the other hand, to validate our numerical results, we carried out a comparison with experimental results [20].
The simulation conditions are:

- The simulation is carried out using the CAST3M computer code.
- The stresses $\Delta\sigma$ applied are: 352 MPa, 282MPa and 248MPa.
- The parameters used to calculate the three-dimensional geometric characteristics involve cubic elements with 8 nodes (Fig.2).
- The tensile force is exerted on the specimen using a rigid triangular device, identified by an arrow, to ensure perfect alignment of the force.
- A quarter of the specimen is modeled, due to the symmetry of the planes.
- All displacements and rotations were set to zero on the axes of symmetry of the quarter specimen examined.

After setting up the numerical model, we carefully considered the mesh sensitivity and convergence criteria to ensure the accuracy of our results. We performed a mesh refinement study to find the optimal element size, ensuring that further refinements didn't significantly affect the outcomes. For the simulations, we used cubic elements with 8 nodes, which

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provided the necessary detail to capture stress concentrations near the notches. To check for convergence, we monitored the residual forces and displacements, making sure they fell below a specified threshold, which indicated that the solution had stabilized. This approach guarantees that our results are reliable and not influenced by mesh size or convergence issues.

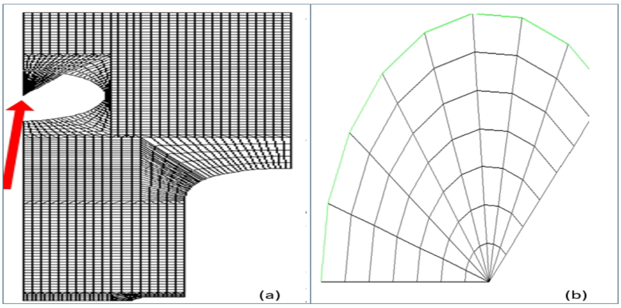

Fig. 2 Specimen mesh: (a) Mesh; (b) Mesh near the notch.

2.3 Tensile behavior under nominal and maximum stresses

The relationship between applied stress and observed strain in the S355 steel test is illustrated in Figure 3, where stress is plotted as a function of strain. The "general shape" of the curve, i.e. the way it appears, indicates ductile behavior of the steel. This ductile behavior is characterized by an elastic zone up to 349Mpa, after which significant progressive plastic deformation before fracture is noticed, the ultimate stress reaching 643Mpa and total strain 22%.

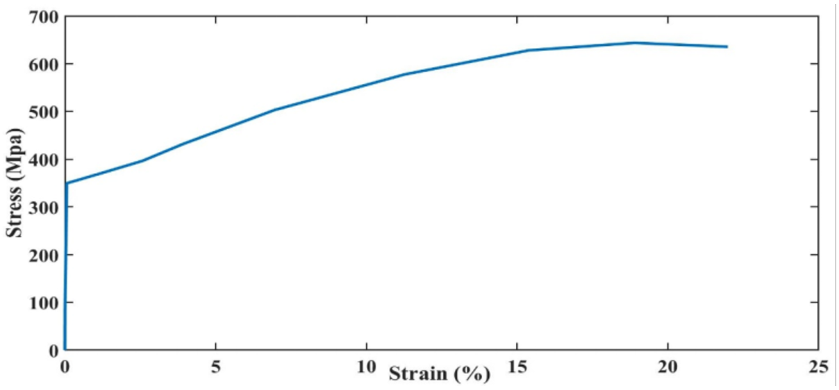

Fig. 3 Experimental characterization curve for S355 steel.

For an applied stress amplitude Δσ, there is a maximum stress and a stress distribution along the tensile stress axis, as well as along the axis perpendicular to the tensile stress, extending from the bottom of the notch to the middle of the width (half-ligament). In all cases, it is verified that the maximum stress lies at σMax at the bottom of the notch. This stress induces a parabolic variation along the ligament to stabilize the nominal stress value σ_{nom}.

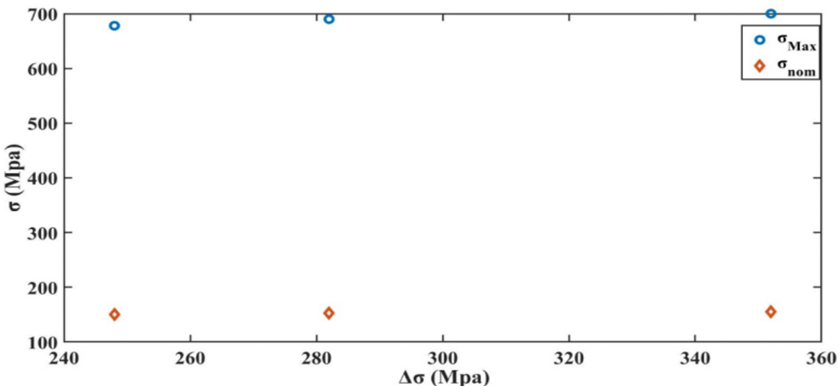

Fig. 4 Numerical values for maximum stress and nominal stress with applied stress.

Figure 4 shows the evolution of maximum, nominal stresses for the three Δσ levels of applied loads. As the applied stress increases, so do the internal forces in the material. S355 steel, being a ductile material, can withstand a gradual increase in stress without breaking immediately. As the applied stress increases, so does the deformation of the material, leading to an increase in the maximum stress observed at critical points, such as the bottom of the notch.
At the same time, the nominal stress, which is a measure of the average stress applied to the specimen cross-section, also increases with applied strain. This occurs because the applied stress is distributed over a reduced cross-section as the strain increases, leading to an increase in the average nominal stress.

2.4 Stress concentration coefficient

Structures are often prone to failure in areas where stresses are concentrated. These zones are generally characterized by discontinuities or irregularities in the part geometry, such as notches or cracks.

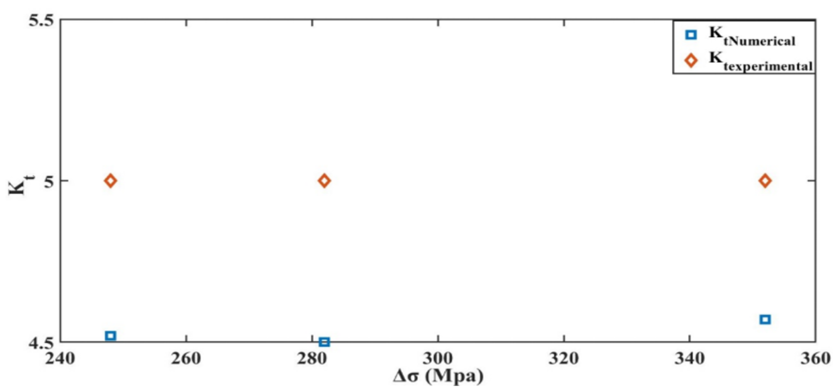

Fig. 5 Experimental and numerical values of Kt as a function of applied load.

In the specific case of CT (Compact Tension) specimens, the notch bottom radius, ρ, plays a crucial role. This radius increases as the stress concentration factor, Kt, decreases. When Kt tends towards 0, this means that the stress concentration factor decreases towards zero, indicating a decrease in the stress concentration effect. In other words, it implies that the material is less likely to experience stress concentration at points such as the bottom of the notch. R. Peterson [21] defined the stress concentration factor, Kt, as a measure of this stress concentration.The stress concentration coefficient is calculated as follows [22]:

$$K_t = \frac{\sigma_{Max}}{\sigma_{nom}} \quad (1)$$

Figure 5 shows the evolution of stress concentration coefficients Kt for three levels of applied load.

2.5 Variation of numerical stress along the horizontal axis of the specimen

Figure 6 shows the variation of numerical stress along the horizontal axis of the specimen for three levels of applied stress $\Delta\sigma$.

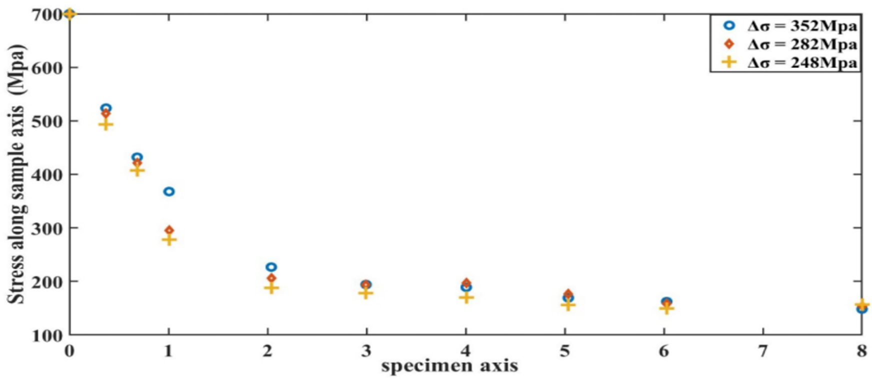

Fig. 6 Numerical stress values along the horizontal axis.

In all three cases studied, numerical simulations reveal that the maximum stress, σ_{Max}, is located near the bottom of the notch. Subsequently, this stress follows a parabolic trend over a range of 0 to 2 mm in order to stabilize the nominal stress value, σ_{nom}. The maximum stress value is attributed to localized plastic flow. Stress concentration near the notch induces plastic deformation in this zone, while zones far from the notch undergo mainly elastic deformation. The stress stabilization at 2 mm is likely due to the plastic deformation that occurs near the notch tip, where the material begins to yield. After this point, the stress distribution becomes more uniform, which reflects the transition from elastic to plastic behavior. This matches what we see in fracture mechanics, especially in relation to the J-integral, which measures the energy release rate during crack growth. As the crack propagates, the J-integral typically increases, showing that the stress near the crack tip intensifies. However, in our case, the stress levels off at 2 mm because a stable plastic zone forms, preventing further stress concentration. This is consistent with what's been observed in other studies, where stress stabilizes after a certain length and the crack propagation becomes more predictable.

3 Conclusion

In this work, CAST3M numerical modeling of the behavior of a double-notched specimen in S355 steel was carried out. The results obtained show that the maximum stress is located at the bottom of the notch, then progressively decreases over a range of 0 to 2 mm. beyond this range, it stabilizes, confirming the validity of our model. The results obtained were validated by comparison with previous numerical experiments and showed good agreement with literature data. This study demonstrates that our numerical approach can be successfully applied in situations where experimental testing would be difficult. This field is highly relevant and is gaining increasing attention. Recently, several researchers have deepened their investigations in this area, bringing new perspectives and significant findings [23-24].

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