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Abstract

People life remains always one of the impressive conditions to be respected essentially if it is connected to very high places. Indeed, for scaffolding lifespan of each part used must be highlighted to respect the 'SAFETY' condition. There are various accidents, even fatal, which have been seen during scaffolding and examples are very numerous following fatigue problem fatigue of uncontrolled parts. This paper focuses on fatigue problem of a part called 'stirrup' commonly used in construction scaffolding. An expertise of existing state part considered took place through mechanical characterization, microhardness as well as finite element modeling. Johnson-Cook model was used to compare the hysteresis curves of two methods namely experimental and that of finite elements (FEM). The numerical technique XFEM was established to model crack growth into Stirrup. Result shows that hardening phenomenon and fatigue (cracks) are the main causes of stirrup premature damage. Crack growth stages were depicted to show fatigue zones as well as crack path and stirrup bending.

Keywords: S235JR; punching; folding; crack growth; failure

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1. Introduction

Scaffolding is a temporary structure on building outside, made of wooden planks and metal poles, used by workmen while building, repairing, or cleaning the building. From ancient times to the present-day, scaffolding is widely used on site to access heights and areas that would otherwise be difficult to access. Unsafe scaffolding can cause death or serious injury. Scaffolding is also used in suitable forms for formwork and shoring, grandstand seating, concert stages, access/observation towers, exhibition stands, ski ramps, halfpipes and art projects. Many problems have been encountered due to carelessness during scaffolding or fatigue of some components of the technique. People live as well as their safety essentially pass through robust scaffolding using parts capable of supporting enormous cyclic loads. There are various techniques used in scaffolding, but the best is the one that uses components with high endurance. Construction companies are increasingly requesting subcontracting and help to create scaffolding; however, work accidents are fatal and disastrous in more than half of cases. This is why monitoring the state of the parts during cyclical loading with enormous forces is an essential step to succeed.

Several researchers have focused on the importance of scaffolding, worker safety, and the lifespan of the process. Indeed, Ewa Blazik et al. [1] presented the attempts at determining the reasons for hazardous incidents which threaten people safety working on scaffolds, as well as in their vicinity.

Kyungki Kim et al. [2] highlighted that scaffolding as a part of the temporary facilities category in construction and must be thoroughly designed, planned, procured, and managed. They developed

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a rule-based system that automatically plans scaffolding systems for proactive management in Building Information Modeling (BIM). Given the importance of studying fatigue phenomenon, many researchers have discussed this problem, emphasizing the role of understanding, analyzing and predicting the parts state after a few cycles. Mendoza et al. [3] used a non-destructive damage evaluation technique for carbon-fiber reinforced polymers (CFRP) using the virtual fields method (VFM). Results showed that specimens with measurable EG (equilibrium gap) signals exhibited considerable interlaminar matrix delamination and flexural failure.

Nirmal et al. [4] investigated the impact behavior of additively manufactured AlSi10Mg alloy and ballistic limit of projectiles using FEM simulations (Johnson-Cook Model).

Welded specimens (S460MC-S460MC joint and S235JR-S235JR joint) were subjected to fatigue tests [5]; It was established that the failure occurred on the base material in all joints had the highest fatigue strength at the most elevated stress, 625 MPa; however, it had the lowest fatigue strength at the lowest priority, 300 MPa. José et al. [6] conducted two-phases of fatigue performance approach based on local strain and Paris law. They showed that fatigue crack initiation as well as propagation phases, combined with numerical simulation, is a suitable method to predict fatigue performance of riveted connections in bridges.

In 2018, Grzegorz Lesiuk [7] and al. developed a new novel energy method which aims to describe the crack growth. The last research results indicated that flaw tip is started by wing crack and followed by secondary crack caused by shear failure. They noticed that elasto-plastic energy approach rises above the disadvantages of the force approach. Xiaojing Li and al. [8] conducted a comparison between experimental analysis and simulative results to describe crack growth and rock specimens' failure.

SOPEM (precision tooling company and mechanical equipment), which seeks to solve a specific problem encountered in the use of a key component in scaffolding, is one of the most companies operating in scaffolding techniques. SOPEM company collaborates with ALTRAD for the manufacture of a product used in scaffolding. This product, known as a keyway collar (or stirrup), is intended to be welded to the railing and is installed in four parts on each floor. ALTRAD claimed a problem recurring affecting collars after use. These essential components for the stability and safety of scaffolding showed signs of cracking and rupture after use period, while others, made from the same Materials, from the same casting batch and the same manufacturing process and subjected to the same conditions of use, remain in good condition. The present work aims to give an expertise of stirrup fatigue which the main objective is to identify these failure causes and to increase its service life. A comparative study including experimental and numerical results to describe crack growth will be conducted in this paper.

2. Material and Methods

2.1. General Context and Problematic

Scaffolding is a modular support system assembled using linear elements interconnected via keyway mechanisms, comprising superposable uprights, connecting and stiffening components, and accessories such as work platforms, consoles, and guardrails. Typically constructed from aluminum for its lightweight and durable properties, scaffolding enables efficient assembly, repositioning, and large-scale elevated work in construction, maintenance, and renovation projects. Professionals must strictly adhere to applicable safety standards to ensure structural integrity and worker protection. Fixed scaffolding is particularly adaptable to irregular surfaces, thanks to adjustable feet, and is available at various heights, with integrated guardrails to prevent falls. A critical component, the stirrup, is used in systems like the VITO 49 to securely attach guardrails to vertical pillars; it engages fully with a light tap on the key, locking the collar in place and preventing unintended movement. However, prolonged use or stress can lead to damage signs, such as cracks along the stirrup edges that propagate through the material, compromising its safety. Once such damage is detected,

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illustrated in Figure 1, the component must be immediately replaced to avoid structural failure and ensure compliance with safety protocols.

Figure 1. Stirrup with damage signs.

This attachment mechanism plays a critical role in preserving the structural stability of the scaffold, particularly when subjected to dynamic loads—such as the movement of workers, the transport of heavy materials, or exposure to environmental factors like wind or vibration. The cleat collar, as a pivotal component, must be engineered to resist a range of mechanical stresses, including shear forces, which act parallel to the surface and can cause slippage or displacement, as well as torsional forces, which induce twisting motions that could compromise the integrity of the connection. To ensure a robust and long-lasting assembly, the collar must be designed with high-strength materials and precision manufacturing, capable of maintaining its grip under fluctuating loads. Additionally, its locking mechanism should provide reliable engagement, prevent accidental disengagement and ensure that the scaffold remains secure even in demanding operational conditions. Regular inspections are essential to detect any signs of wear, deformation, or fatigue, as these could undermine the collar's performance and, consequently, the overall safety of the scaffolding system.

2.2. Manufacturing Process

The raw material used in this manufacturing process is hot-rolled S235JR steel, a non-alloy structural steel known for its excellent weldability, machinability, and mechanical properties, making it ideal for structural applications. This steel is supplied in the form of castings, with each casting containing 10 individual coils. These coils are produced to specific dimensions, ensuring consistency in thickness, width, and weight to meet the precise requirements of downstream processing.

Once delivered, these coils serve as the primary input material for subsequent cold forming operations. Cold forming is a highly efficient manufacturing process that involves shaping the steel at room temperature, which enhances its strength, surface finish, and dimensional accuracy without altering its material properties. The coils undergo a series of processes, such as uncoiling, straightening, cutting, and forming, to produce components with tight tolerances and superior structural integrity. This method is particularly advantageous for creating complex geometries while maintaining material uniformity and minimizing waste. The resulting cold-formed steel components

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are widely used in construction, automotive, and industrial applications due to their high strength-to-weight ratio and durability.

2.2.1. Breakdown (Cutting)

The shearing process illustrated in Figure 2(a) involves the precise cutting of sheet metal using a mechanical action where the material is securely held between a punch and a die. As the punch descends into the die, it exerts a concentrated force that severs the material, analogous to the action of scissors but with significantly greater precision and control. This process is critical in manufacturing, as it enables the production of components with clean edges and consistent dimensions.

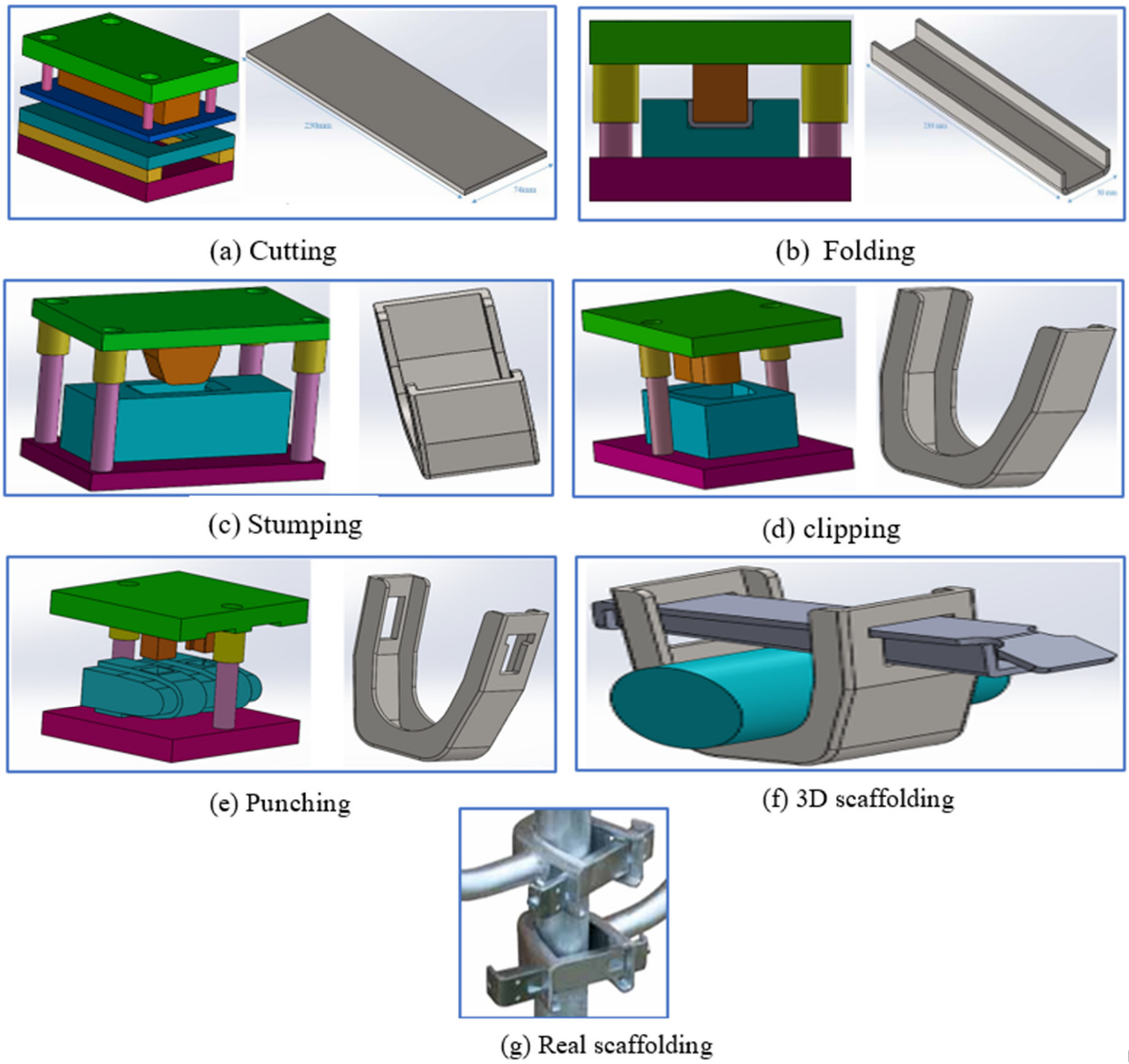

Figure 2. Making stirrup steps before use.

The cutting force required for this operation is substantial, measured at approximately 36,966 decanewtons (daN), reflecting the high resistance of the material being sheared. To ensure the efficiency and longevity of the tooling, it is imperative to maintain an optimal punch-die clearance. This clearance—the gap between the punch and die—must be carefully calibrated to prevent issues such as excessive gripping, which can lead to tool wear or deformation, or die rupture, which may result in costly downtime and repairs.

Proper clearance not only safeguards the tooling but also plays a pivotal role in achieving a high-quality finished product. It ensures clean, burr-free edges and dimensional accuracy, both of which are essential for downstream processes such as assembly or further machining. Additionally, maintaining the correct clearance helps minimize material distortion and tool stress, ultimately contributing to the precision, repeatability, and overall efficiency of the shearing operation. Regular inspection and adjustment of the clearance are therefore essential to sustain both product quality and operational reliability.

2.2.2. Bending U-Shape

Folding, shown in Figure 2b, allows obtaining developable parts whose folds are obligatory rectilinear. The U-fold force in the present work is about 42658 N. Press U bending refers to a process in which the sheet is constantly bent over bending press twice or more to get "U" shape. This process is accomplished by precisely controlling closing degrees of upper and lower dies and strokes to meet precise size and angle requirements of the design. U-bending is one of the most common forming techniques in metal manufacturing industries. Latter process not only reduces material costs and improves production efficiency but also ensures good mechanical properties and appearance quality of products. U-bending technology is constantly updated with press evolution brake technology, which ranges from simple straight-line folding to three-dimensional folding. It not only improves the apparent bending angle and accuracy but also achieves automatic constant folding in several steps.

2.2.3. Stumping

The stamping process depicted in Figure 2c is a cold plastic forming method applied to metal sheets, where the stirrup's complex geometry—characterized by sharp angles, curves, and pre-formed folded sections—poses significant challenges compared to simpler, flat shapes. During stamping, these folded areas, having already undergone plastic deformation in earlier stages, retain residual stresses that can lead to uncontrolled deformations or cracking when further pressure is applied, especially in high-stress zones where material integrity is most vulnerable. To counteract these risks, the process demands precision-engineered dies and specialized tooling, meticulously designed to conform to the folded shape while minimizing defects such as cracks or tears that arise from stress concentration. Unlike flat geometries—where stress distribution remains uniform and tooling requirements are simpler—folded shapes introduce asymmetrical stress patterns, increasing the likelihood of structural weaknesses and requiring rigorous monitoring to ensure quality. The uneven stress distribution in folded designs not only complicates the stamping process but also heightens the risk of post-forming defects, such as crack propagation, which can compromise the part's long-term performance. Thus, while flat shapes benefit from simpler tooling and more predictable outcomes, stamping intricate geometries like the stirrup necessitates advanced stress analysis, tailored tooling, and precise process control to achieve a defect-free and structurally sound final product.

2.2.4. Clipping

Clipping, as illustrated in Figure 2d, is a precision trimming operation designed to remove excess material from the perimeter of a stamped or formed part, ensuring it achieves the exact dimensional and geometric specifications required for its intended application. This process is particularly critical in sheet metal fabrication, where preceding manufacturing stages—such as deep drawing, bending, or stamping—often leave irregular edges, burrs, or surplus material along the part's contour. These imperfections, known as "coast return" or flash, result from material flow and deformation during forming and must be eliminated to meet tight tolerances and functional requirements.

Clipping serves as a finishing step that refines a previously rough or distorted contour, transforming it into a clean, precise profile. By systematically trimming away unwanted material, the operation enhances the part's dimensional accuracy, surface quality, and overall fit, making it suitable for subsequent assembly or direct use in final applications. Whether performed as an in-die cutting process during stamping or as a secondary post-press operation, clipping plays a pivotal role in converting a raw stamped blank into a high-precision component that adheres to strict engineering standards. Without this step, residual excess material could compromise part functionality, assembly compatibility, or aesthetic quality, particularly in industries such as automotive, aerospace, or construction, where precision and reliability are paramount. The effectiveness of clipping directly impacts the performance, safety, and longevity of the finished product, underscoring its importance in modern metalworking processes.

2.2.5. Punching

Punching, depicted as the final manufacturing operation in Figure 2e, is a high-precision process used to add intricate details—such as holes, slots, or custom cuts—to preformed parts with exceptional accuracy. This operation involves a punch, a hardened tool that forcibly removes a defined section of material from a sheet metal workpiece or strip, while a die provides support and ensures clean separation. Punching is renowned for its speed, efficiency, and cost-effectiveness, making it a preferred method for producing high-quality features without the need for expensive tooling or secondary operations. The simplicity and affordability of punching tools further enhance its appeal, offering manufacturers a budget-friendly solution for achieving precise, repeatable results in mass production.

In the context of scaffolding components, punching is employed to create functional recesses, such as the two strategically placed cutouts in the stirrup, enabling seamless integration with other scaffolding elements. Following these forming processes, components may undergo galvanization to enhance corrosion resistance, while others are dispatched in their raw state, depending on their intended application and environmental exposure.

Figure 2f highlights additional critical scaffolding components: a key and a 48.8 mm diameter cylinder, both essential for structural stability and operational safety. However, despite their robust design, these components—particularly the stirrup (collet)—are subjected to intense mechanical stresses during use, as illustrated in Figure 2g. Over time, repeated cyclic loading can induce fatigue, leading to the formation of micro-cracks that propagate under operational strains. These cracks not only compromise the structural integrity of the stirrup but also pose significant safety risks, particularly in high-altitude work environments where scaffolding failures can result in catastrophic accidents.

The emergence of cracks necessitates immediate intervention, often causing unplanned work stoppages and costly downtime for repairs or replacements. Fatigue-induced degradation underscores the importance of regular inspections, preventive maintenance, and material quality control to mitigate risks and ensure the longevity and reliability of scaffolding systems. Ultimately, the safety of workers operating at height depends on the durability and resilience of these components, making fatigue resistance and structural monitoring critical priorities in scaffolding design and maintenance.

2.2. Material Characterization

The stirrup under examination is constructed from S235JR steel, a low-carbon, non-alloy structural steel renowned for its versatility, weldability, and mechanical strength, with its chemical composition precisely outlined in Table 1 and verified through stationary SPECTROMAXx spectroscopic metal analysis to ensure elemental accuracy. As a material compliant with EN 10025-2 standards, S235JR is extensively employed across a wide range of industries, including industrial piping and pipelines for gas and oil transport, marine applications such as shipbuilding, agricultural machinery requiring durability, construction equipment like beams and scaffolding, and pressure vessel manufacturing, where its ability to withstand internal pressures is critical [9]. The steel's performance is significantly enhanced by its chemical composition, particularly the presence of copper (Cu) and manganese (Mn); copper improves corrosion resistance and longevity in challenging environments, while manganese boosts hardness, tensile strength, and wear resistance, ensuring the

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material can endure mechanical stresses and cyclic loading without premature failure. This balanced combination of properties—coupled with its cost-effectiveness, machinability, and formability—makes S235JR an optimal choice for structural components like the stirrup, where safety, precision, and long-term reliability are essential to maintaining operational integrity in demanding applications.

Table 1. Chemical composition of S235JR steel.

Chemical composites	**S234 JR steel**
C	0.040
Si	0.018
Mn	0.232
P	0.015
S	0.017
Cr	0.098
Ni	0.111
V	0.001
Al	0.031
Cu	0.409
Nb	0.001
Ti	0.001
Fe	balance

Understanding the mechanical properties of materials, such as S235JR steel, is critical for both engineering design and numerical simulations, as these properties define how a material behaves under stress, including its stiffness, elongation, toughness, and resistance to mechanical loads, all of which are essential for predicting performance in real-world applications. To obtain these properties, three standardized test samples—shown in Figure 3a—were prepared, with their dimensions, including the active gauge length, detailed in Figure 3b to ensure consistency with prior results. Testing was conducted using a tensile machine (Figure 3c), where each sample was subjected to a controlled tensile force until fracture (Figure 3d) under room temperature conditions (298 K) and a constant loading velocity to maintain accuracy. The resulting stress-strain curve (Figure 3e) reveals three key phases: the elastic deformation zone (AB), where the material deforms reversibly; the plastic deformation zone (BC), where permanent deformation occurs; and the rupture zone (CD), where the material ultimately fails after reaching its maximum resistance. This curve confirms that S235JR steel exhibits an average yield strength of approximately 357 MPa, aligning with its classification as a low-carbon structural steel. The primary goal of these mechanical tests is to quantify material properties—summarized in Table 2—which are then used in strength calculations and Finite Element Method (FEM) simulations to ensure structural reliability and performance optimization in engineering applications.

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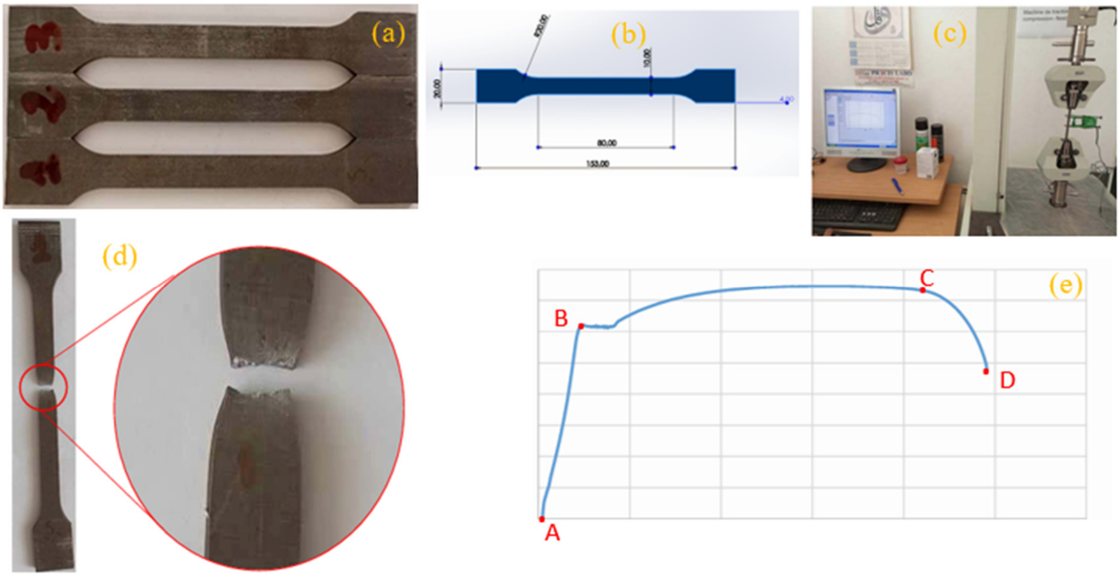

Figure 3. Tensile test machine.

The Johnson–Cook (JC) model, introduced by G.R. Johnson and W.H. Cook in 1983 [10], is an empirical and phenomenological constitutive model that has gained widespread recognition for its ability to accurately describe the stress-strain relationship and thermo-viscoplastic behavior of materials, including S235JR steel. What sets this model apart is its simplicity, robustness, and ease of implementation, coupled with the relative accessibility of its material constants, which can be experimentally determined through standardized mechanical tests. These characteristics make the Johnson–Cook model a preferred choice for engineers and researchers seeking to simulate and predict material behavior under extreme conditions.

One of the key strengths of the Johnson–Cook model is its versatility in accounting for multiple influencing factors, such as high strain rates, large deformations, and elevated temperatures. This capability is particularly valuable in dynamic loading scenarios, such as impact, explosion, or high-speed machining, where materials are subjected to rapid deformation and thermal effects. By incorporating these parameters, the model provides a comprehensive framework for analyzing how materials respond to complex, real-world conditions, ensuring that predictions remain reliable and physically meaningful.

The mathematical formulation of the Johnson–Cook model, as presented in equation (1), expresses the flow stress as a function of strain, strain rate, and temperature. This relationship allows researchers to quantify the material's resistance to deformation under varying conditions, making it an indispensable tool for finite element analysis (FEA), crash simulations, and ballistic impact studies. Due to its proven accuracy and computational efficiency, the Johnson–Cook model has been extensively adopted by the scientific community to predict the flow behavior of a wide range of materials, from metals and alloys to composites and polymers.

In the context of S235JR steel, the Johnson–Cook model is particularly useful for evaluating its performance in high-strain-rate applications, such as automotive crash structures, industrial machinery, and scaffolding systems, where dynamic loading and thermal effects play a critical role. By leveraging this model, engineers can optimize material selection, refine structural designs, and enhance safety margins, ultimately contributing to the development of more resilient and efficient systems. The model's empirical nature also allows for continuous refinement as new experimental data becomes available, ensuring its ongoing relevance in both academic research and industrial applications.

$$\sigma=(A+B\varepsilon^{n})\left(1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{r}}\right)\left(1-\frac{T-T_{r}}{T_{m}-T_{r}}\right)^{m} \quad (1)$$

where A is the yield stress, B is a material constant, n is the hardening coefficient, C is the stress-strain sensitivity, m is the temperature coefficient, $\dot{\varepsilon_0}$ is the reference strain rate and $\dot{\varepsilon_p}$ is the plastic strain rate. T is the current temperature; Tr is a reference temperature and Tm is a reference melt temperature. Johnson-Cook model parameters are defined in Table 2.

In equation (1) and from left to right, the first term characterizes the elastoplastic behavior of Ludwick's law (the strain hardening effect). The second term considers the visco-plasticity (strain rate strengthening) and finally, the third term quantifies the temperature effect on behavior of the material.

In respect of the experimental conditions, the reference strain rate, $\dot{\varepsilon}_r$, and the reference temperature, Tr, were taken as 1298 K and 1.0 s^{-1}, respectively. Johnson and Cook approved that fracture strain mainly depends on stress triaxiality ratio, strain rate and the temperature.

The Extended Finite Element Method (XFEM) represents a powerful advancement over the traditional Finite Element Method (FEM), specifically designed to simulate complex fracture mechanics phenomena, including crack initiation, propagation, and branching in materials. Within the ABAQUS simulation environment, XFEM is implemented as an Interaction Model, enabling engineers and researchers to accurately model dynamic crack behavior under various loading conditions. Unlike conventional FEM, which requires explicit mesh refinement around crack tips and frequent remeshing as cracks evolve, XFEM eliminates these computational limitations by introducing enrichment functions directly into the finite element formulation.

In ABAQUS software, these enrichment functions are integrated to capture discontinuities—such as cracks, voids, or material interfaces—without altering the underlying mesh structure. This is achieved through the use of specialized shape functions that incorporate discontinuous fields and asymptotic crack-tip fields, allowing for the realistic representation of crack growth along arbitrary, unpredictable paths. The key advantage of XFEM lies in its ability to simulate crack propagation independently of the mesh, meaning that cracks can initiate and extend freely through the material without requiring manual mesh adjustments or computationally expensive remeshing procedures. This feature not only reduces simulation time and complexity but also enhances the accuracy of predictions, particularly in scenarios involving complex geometries, heterogeneous materials, or dynamic loading conditions.

By leveraging XFEM, engineers can study fracture mechanics in greater detail, including stress intensity factors, crack growth rates, and failure modes, which are critical for assessing structural integrity in applications such as aerospace components, automotive safety systems, civil infrastructure, and mechanical assemblies. The method's versatility also extends to multi-physics simulations, where thermal, mechanical, and environmental effects interact to influence crack behavior. Ultimately, XFEM provides a robust and efficient tool for predicting and mitigating material failure, enabling the development of safer, more durable, and optimized designs across a wide range of industries.

Table 2. Mechanical properties and Johnson cook parameters of S235JR [11,12].

Description	**Notations**	**Value**
Young Modulus	E	209 GPa
Poisson's ratio	ν	0.3
Density	ρ	8587 Kg/m^3
Tensile strength	R_m	426 MPa
Elongation	A%	35

yield stress	Re	357 MPa
Yield stress constant	A	480 MPa
Strain hardening	B	153 MPa
Constant	n	0.36
Viscous effect	C	0.0141
Thermal softening constant	m	1.3
Reference strain rate	$\dot{\varepsilon}_0$	1 s^{-1}
Melting temperature	T_m	1773 K
Reference temperature	T_r	1298 K

3. Results and Discussion

3.1. Experimental Results

Moving from industrial problem to experimental or numerical simulation in laboratory remains a very difficult task to succeed. To effectively analyze and understand the defects of a system, it is essential to apply the same loads and boundary conditions as those in the real case. For this, problem simplification, without neglecting what really happens, should take place. In scaffolding, stirrup is used with a rod to combine two axes. In laboratory, as shown in Figure 4, stresses were considered with some modifications to remain always close to the studied real case. Tensile machine was used to conduct tensile-compression test to stirrup part. Choice of suitable parameters for this test such as loading force value, speed is a crucial step which shouldn't be exceeded.

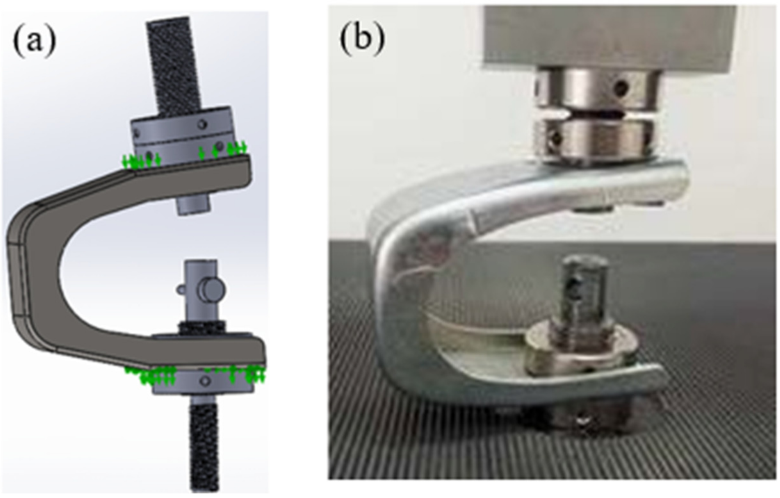

Figure 4. Laboratory simulation conditions for stirrup without axis; (a) 3D case (b) Real case.

In the field of metal fatigue, service life is divided into two main phases namely crack initiation and propagation [13,14]. The tests were carried out in the laboratory using tensile machine. This latter was equipped with clamping parts (threaded rod and nut) and a 45 kN load cell was used. Two cyclic compression-decompression (tension) tests were carried out, like the action of striking key to move it and fix cylinder by conical shape. Thus, the part is subjected to compression, and cylinder in the middle, clamped by key collar, reacts with opposite compression (Figures 4a and b). This is like a tensile test.

In first step, a test without a cylinder was carried out with a strain rate of 100 mm/min, over several about 1000 cycles. Stresses applied during test are of the sinusoidal type. By applying a load of 5000 N for limit cycle 1 and -5000 N for limit cycle 2 as shown in Figure 5a. The end of each test is marked by crack appearance and its propagation. Currently, after 286 cycles, already mentioned signs appear which requires experiment close.

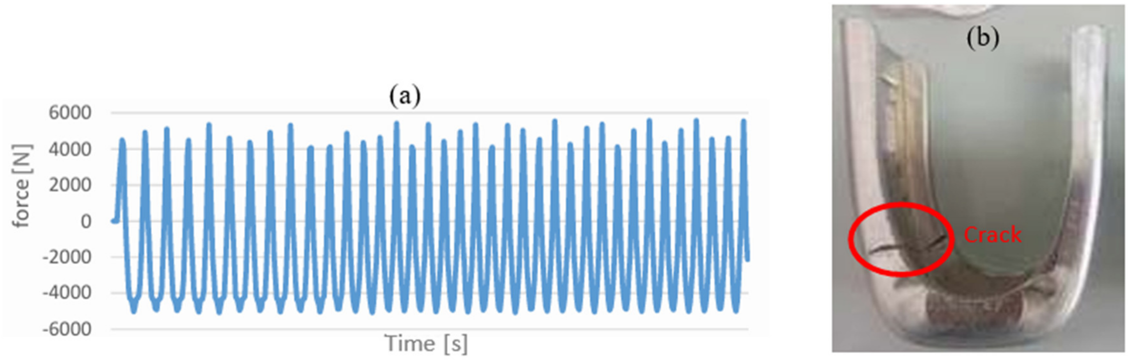

Figure 5. Tensile-compression test without axis using tensile machine; (a) Force-time curve (b) Stirrup fatigue.

For the second test, an axis with a 53 mm diameter—matching the standard dimensions used in scaffolding—was employed to replicate real-world conditions. The experiment was conducted at a deformation speed of 200 mm/min, chosen to accelerate testing while maintaining controlled conditions. Over approximately 1,000 cycles (Figures 6a and 6b), the test aimed to simulate repetitive operational stresses, such as those caused by worker movement or environmental vibrations. This approach allowed for an efficient yet accurate assessment of the material's fatigue behavior, crack initiation, and structural integrity under prolonged cyclic loading.

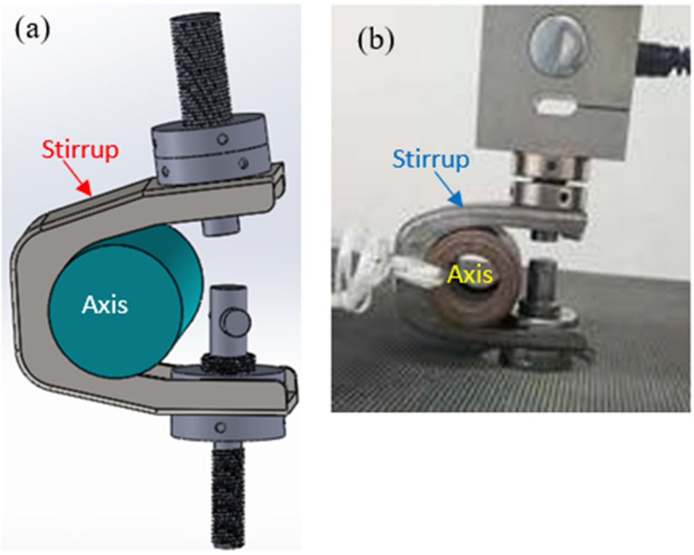

Figure 6. Laboratory simulation conditions for stirrup using axis; (a) 3D case (b) Real case.

By applying a load of F= 5000 N for limit cycle 1 and F= -5000 N for limit cycle 2 as shown in Figure 7a. It is noted that the part (stirrup) reached rupture after 660 cycles in the zone as illustrated in Figure 7b. From the two tests carried out in fatigue study, it was noticed that product (stirrup) presents damage (Crack) in the same area. However, cylinder axis allows them to increase their service life, since the test without cylinder supports less load before plastically deforming or developing cracks, which reduces their number of cycles.

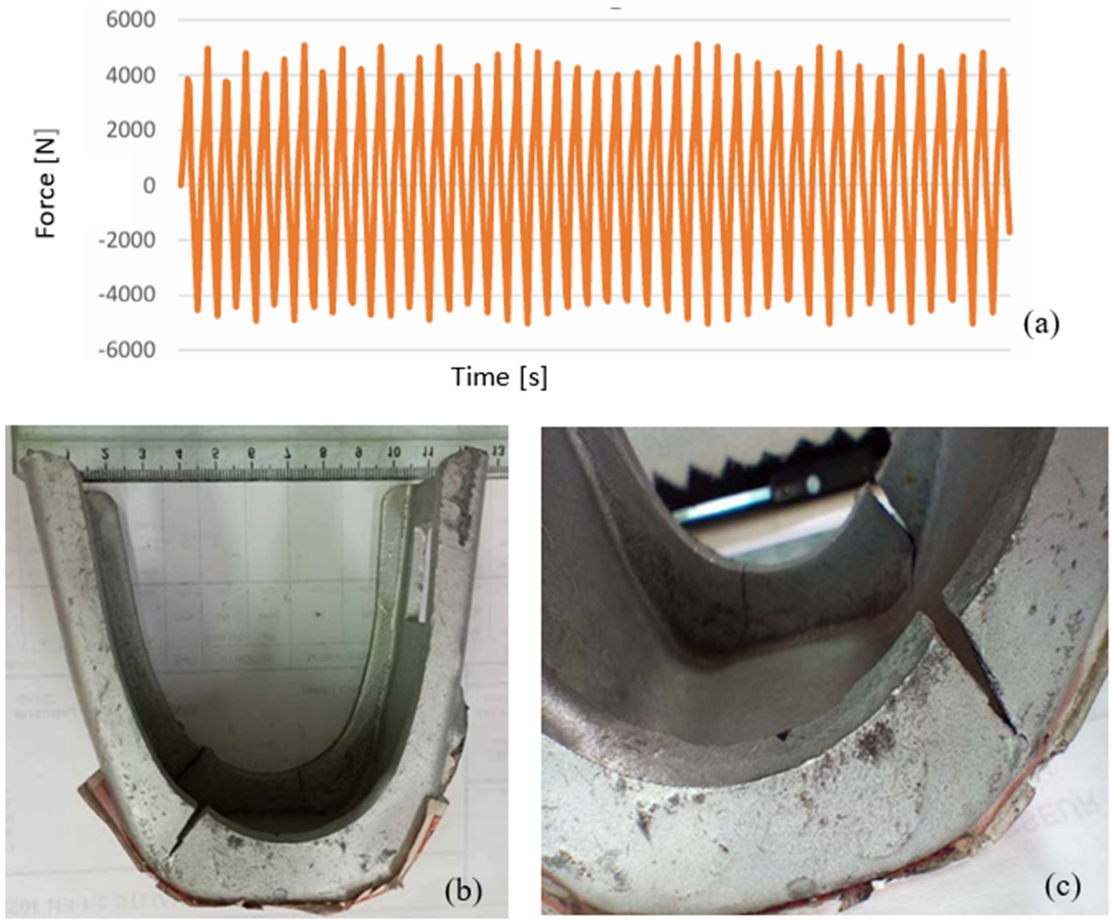

Figure 7. Tensile-compression test with axis using tensile machine; (a) Force-time curve; (b) and (c) Stirrup fatigue (cracks).

Figure 8 Shows a transverse crack at the stirrup. It seems to spread perpendicularly to loading direction. The crack can cause the stirrup to fracture into two separate pieces, thereby preventing its continued use in scaffolding structures. Five micro-hardness tests Hv were carried out near crack zone. The curve (Figure 8) presents micro-hardness measurements results. Indeed, these latter show a peak for the second test (~134 hv) which is the result of the test closest to crack. Micro-hardness decreases in low toughness zone by gradually moving away from macro-crack. This result can be explained by hardening phenomenon approved by [15,16] when studying microhardness and microstructure of different steels hardened by a fiber laser. Thus, following cyclic loading (compression-traction) exerted on the stirrup, micro-hardness of stress-concentration area increases and subsequently hardening has taken place. In this way, cracks tend to appear, propagate and reunite to separate stirrup piece into two parts. Following last result, stirrup is no longer suitable now to support scaffolding forces. The need to install an additional component creates both a practical inconvenience for workers and a potential safety hazard that should be mitigated.

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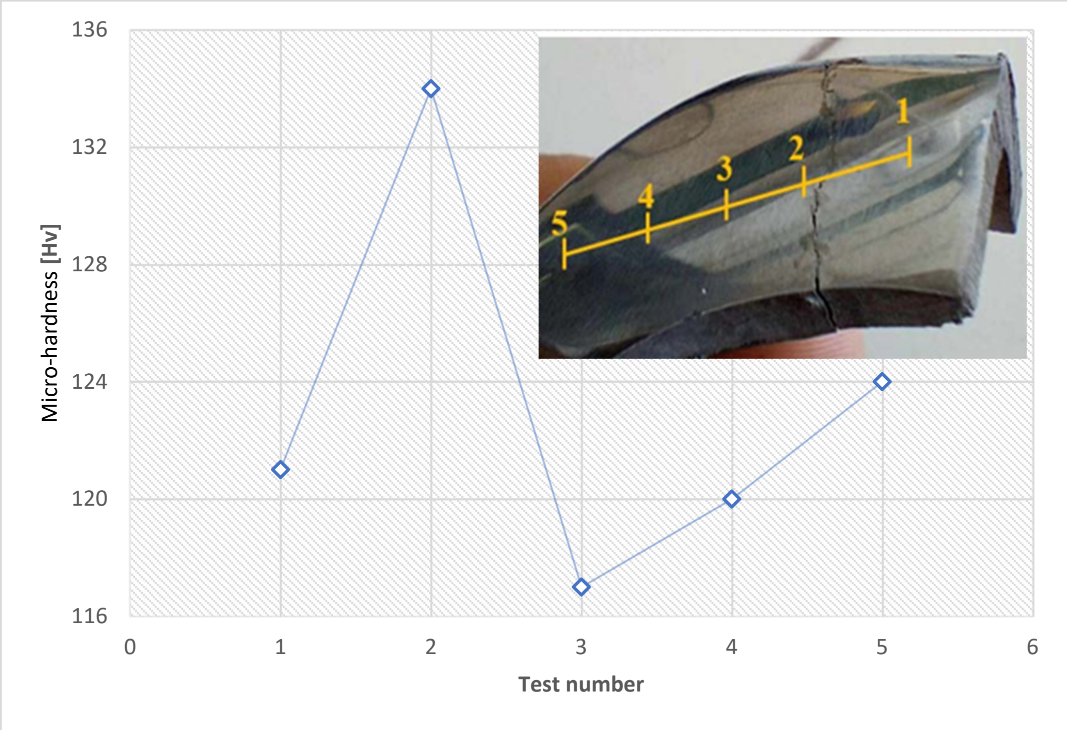

Figure 8. Stirrup microhardness-test.

3.2. Numerical Results

Numerical simulation offers a low-cost alternative for obtaining reliable results without the necessity of conducting physical experiments. The results of simulation are highly recognized by researchers in the industrial world. Understanding the fatigue phenomenon in the material can be achieved through crack growth study. In fact, ABAQUS software was used, using the finite element method (FEM) and under the heading 'XFEM'. This method allows mechanical stress on the one hand and cyclic loading on the other hand. The initiation phase is the first one that occurs during crack growth. This phase begins following material fatigue under cyclic stresses and excessive loads during scaffolding. Geometric or microstructural defects, as well as weak zones created by imperfections and stress concentrations, can give rise to this crack. As shown in Figure 9, the crack occurs in the opening mode with a somewhat lengthy process since it depends mainly on internal factors such as hardness and Young's modulus of S235JR and other external factors such as the environment, humidity, temperature, and usage rate (number of cycles). This first phase is very difficult to detect during use, which represents an inevitable danger.

In multi-cycle fatigue scenarios, crack initiation tends to be a gradual process and is often challenging to detect during its initial phase.

Following crack initiation, the process enters the propagation phase, known as the 'stable crack growth phase.' In the stirrup, the crack advances incrementally with each load cycle. This phase can be further divided into two sub-stages, each characterized by distinct propagation behavior. The first phase is generally influenced by the material's microstructure and results in short cracks [17,18]. These join to form longer cracks. The second sub-phase represents a high growth rate with longer and more stable cracks. The crack present in the stirrup is the result of in-service fatigue, as it is a material with ductile fracture. In the present phase the stable crack growth is slowly controlled; indeed, the crack propagates under fixed rate when load is increased. Besides, in this case, sudden failure doesn't occur since the material is able to absorb energy. The crack length increase but it doesn't enter on unstable field, and it occurs without rapid acceleration. The crack size doesn't reach a critical value and material ability to absorb energy is not exceeded. Figure 10 shows what has just been said. Currently, despite the increase in Von Mises stress, which reflects the increase in cyclical loading, the crack does not lead to damage or catastrophic failure. In this stage of crack propagation, the stirrup retains its functional integrity, maintaining operator safety on the scaffolding structure. Nevertheless, vigilance is required, as the crack can quickly progress into the unstable propagation phase, posing a potential risk.

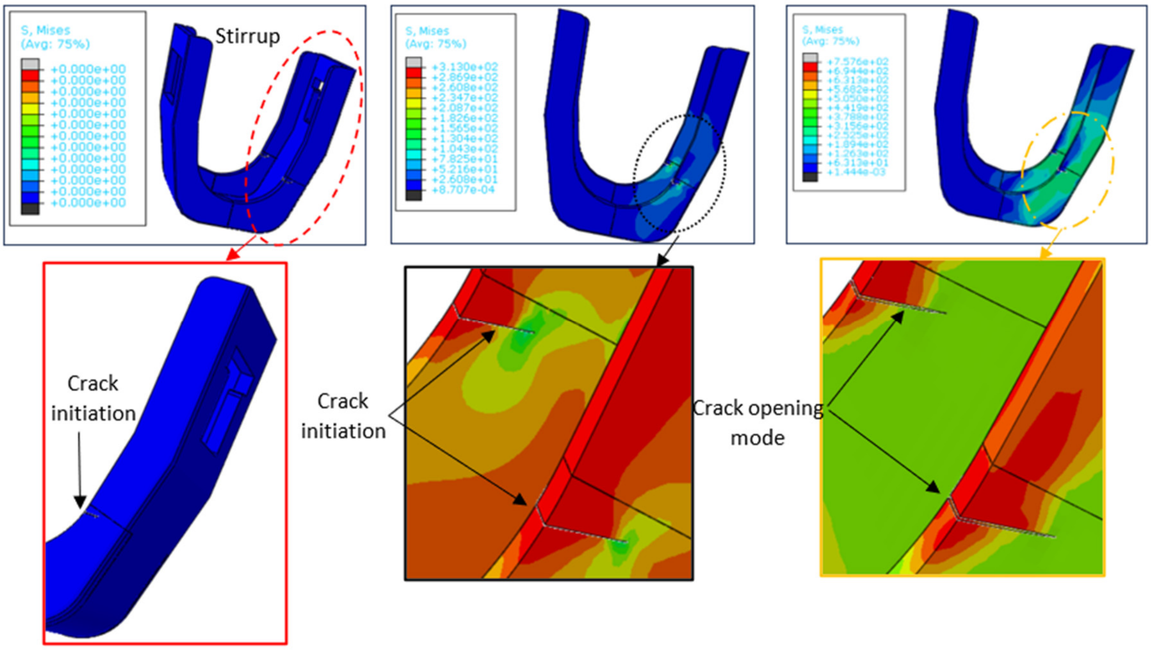

Figure 9. Crack initiation stage in stirrup part.

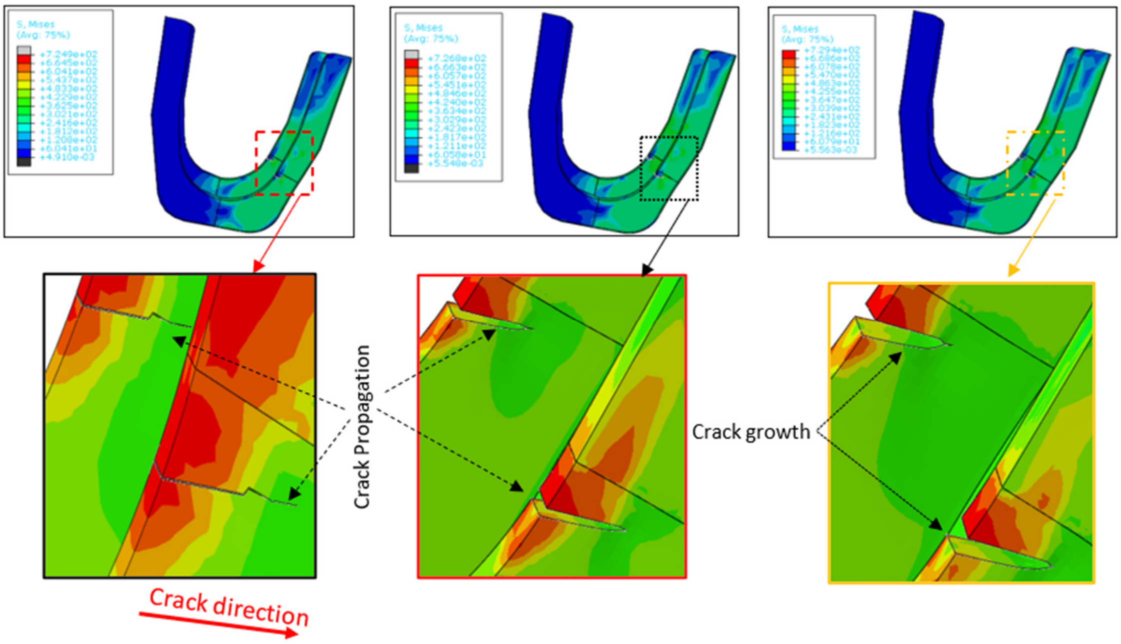

Figure 10. Crack propagation in stirrup: Stable crack growth.

Following the stable crack growth phase, the crack transitions into an unstable state. If it reaches a specific threshold referred to as the 'critical crack size', catastrophic failure may ensue.Upon reaching the unstable growth phase, the crack propagates rapidly through the grain boundaries of the material or by dissociating the grains themselves which was conducted by Chai et al. [19] using acoustic emission and Zhang and collaborates [20] throw CJP Model (Christopher James Patterson model). Material toughness in this phase is exceeded by the local stress near the crack. In the case of the S235JR stirrup, crack propagation is unpredictable both in size and direction, which inevitably

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results in failure of the component. A dramatic and rapid crack acceleration can occur, generating new fracture surfaces and greatly diminishing, or entirely negating, the material's ability to absorb energy. This type of cracking occurs with little warning, so the lives of stirrup users can be in danger. Given that human life is a paramount consideration in all engineering projects, controlling the unstable phase of crack propagation is essential to mitigate risks and ensure safety. As shown in Figure 11, from a Von Mises stress of 735 MPa the folding phenomenon begins to appear on the part subjected to intense cyclic loading. At the periphery of the crack, stress concentration and geometric constriction zones develop, which play a key role in promoting crack propagation. Following stress concentration, work hardening is induced, leading to the generation of dislocations that first appear on the surface of the steel and progressively develop throughout the bulk of the stirrup. An anti-plane shear mode (mode III) seems to be occurring. Once this stage of crack propagation is reached, the stirrup can no longer reliably support the applied loads in the scaffolding system. Therefore, it is essential to avoid the transition into unstable crack growth.

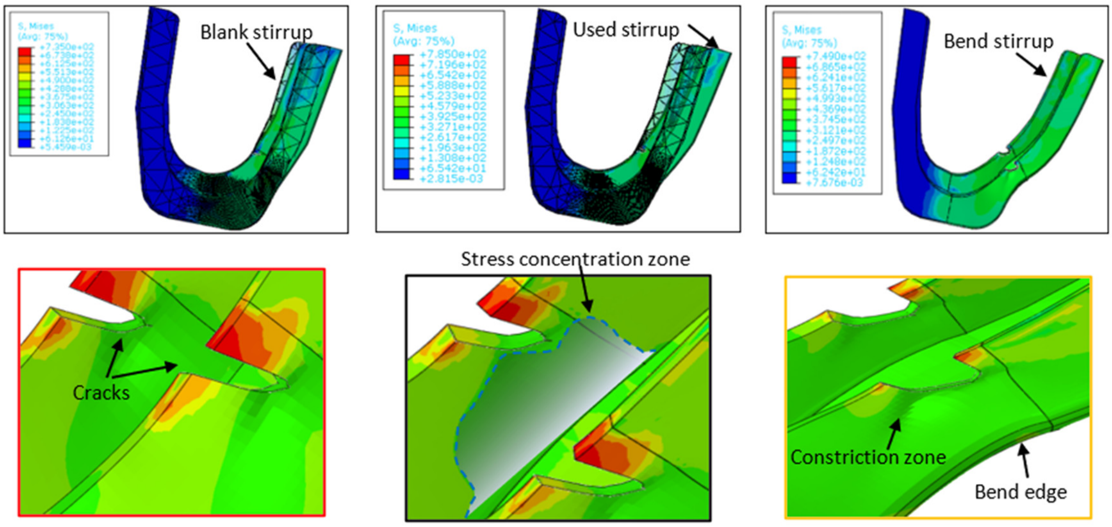

Figure 11. Crack propagation in stirrup: Unstable crack growth.

The following section details the final rupture phase of the stirrup. Indeed, as shown in Figure 12, The loaded region undergoes bending, leading to the emergence of striations and localized stress concentrations. The increased crack size compared to its initial state has contributed to the enhanced deformation of the stirrup. Crack propagation occurs in both stable and unstable states, confirming the damage and eventual failure of the component. Consequently, the part is no longer fit for service and requires replacement. To conclude, analyzing crack growth, including initiation and propagation phases, provided valuable insights into the stirrup's in-service behavior and a comprehensive understanding of the crack propagation mechanisms across all stages.

The stirrup was loaded under displacement control with an amplitude of 11 mm. This loading induced plastic deformation in the stirrup, with hysteresis curves reflecting the influence of stress concentration. In Figure 13, following crack initiation on the stirrup, a rapid increase in the softening zone intensity was observed, culminating in the ultimate failure of the specimen. The stirrup was subjected to a cyclic load varying between -6000 N (compression) and 6000 N (tension). The specimen underwent compressive loading over the entire displacement range before entering the tensile phase, with this loading sequence alternating continuously. As shown in Figure 13, hysteresis curves of both numerical and experimental techniques are displayed. Numerical and experimental tests agreed in terms of crack size and path which give good reproducibility. Nevertheless, a slight discrepancy between the two tests was noted, likely due to experimental uncertainties inherent in the physical testing and the reliance on numerical parameters obtained from literature for the simulation.

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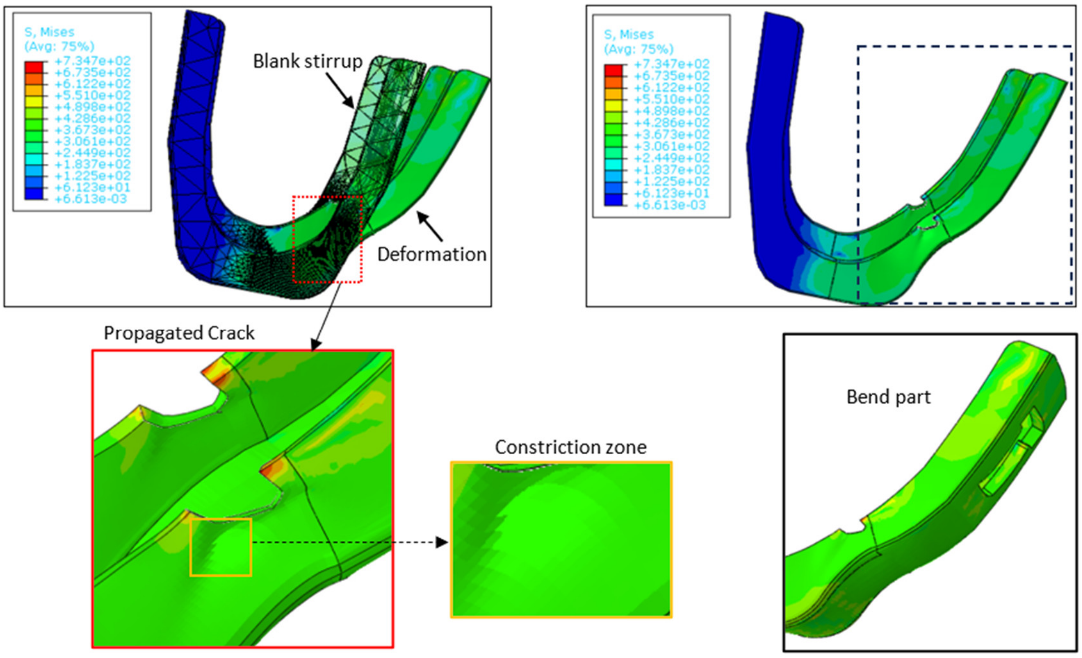

Figure 12. Stirrup with failure signs.

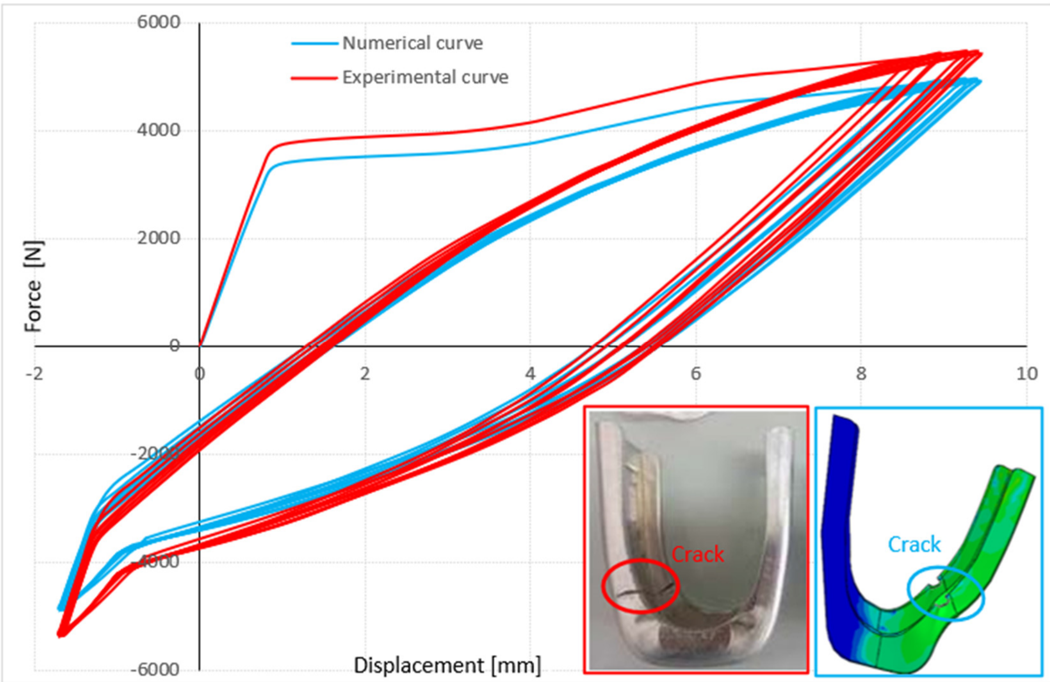

Figure 13. Numerical and experimental hysteresis curves under Compression-tensile loading.

3. Conclusion

In this study, an evaluation of the existing state of the stirrup was conducted. The manufacturing process of the part was examined to better understand and pinpoint the regions experiencing stress under load. XFEM method was inserted into ABAQUS software to describe crack growth stages. The Johnson-Cook model was used to compare experimental and numerical findings related to hysteresis behavior. While the stress concentration zones under compression-tension loading were similar in both cases, discrepancies were noted in key parameters such as the maximum stress magnitude and the number of cycles endured prior to damage. All crack growth were described with all stages and stress concentration zone and fatigue were fixed. The subsequent section of this paper is dedicated to investigating different fracture phenomena through the application of the Johnson-Cook failure model. Status of XFEM (STATUSXFEM) such as (PHILSM/PSILSM) will be presented to define crack extent and crack location.

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