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Pre-Fatigue Damage and Its Impact on Mechanical Performance of High-Strength Steel: A Critical Review

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Abstract: High-strength steel is susceptible to fatigue damage during service, which alters its internal microstructure and subsequently affects its mechanical performance. This study explains the related damage mechanisms in high-strength steel, presents a methodical comparison of conventional fatigue and pre-fatigue, and describes how to assess pre-fatigue situations in order to better comprehend these impacts. Additionally, it looks at how pre-fatigue affects hysteresis behavior, static tensile characteristics, and overall fatigue performance. A technique to evaluate the mechanical performance of high-strength steel that has had pre-fatigue damage is suggested based on these observations. The findings show that pre-fatigue causes microstructural changes that hasten the development of early-stage damage. This reduces yield strength, ultimate tensile strength, and ductility when loaded. It also promotes earlier fracture initiation and faster crack propagation, which ultimately shortens fatigue life. Pre-fatigue also reduces the material's ability to dissipate hysteretic energy in steel structures that already exist. In order to support deeper understanding and future developments in this field, the study finally expands its analysis to the post-pre-fatigue mechanical response of high-strength steel, taking into account the combined influence of environmental conditions, machine learning-based damage evaluation approaches, and multi-scale, interdisciplinary analysis.

Index Terms -: Fatigue fracture, High-strength steel, Mechanical properties, Crack initiation, Microstructure.

1. INTRODUCTION

Urban infrastructure has grown quickly in recent years, which has led to the design of structures that are bigger, lighter, and more advanced. This change puts more emphasis on how well materials work overall, especially how strong and long-lasting they are, and it creates new problems for modern steel design methods and building methods [1-2]. High-strength steel (HSS) is a type of steel that has a nominal yield strength of more than 460 MPa. It has a number of advantages over regular structural steels, such as being stronger, more resistant to corrosion from the air, and easier to weld. In addition to meeting strict load-bearing requirements and providing significant economic and societal benefits, these characteristics enable less structural weight, more effective use of space, and enhanced energy efficiency and sustainability [3]. However, HSS components are frequently subjected to repetitive loads from sources including traffic, wind, and wave action under complex operating circumstances. Such cyclic loads may not cause obvious damage right away, but they might eventually cause fatigue in the material, which will shorten its lifespan. Therefore, enhancing the durability and dependability of structural systems requires a detailed evaluation of how pre-existing fatigue damage affects the mechanical performance of HSS [4].

Even in the early phases of their service life, steel buildings frequently suffer varying degrees of fatigue damage. This damage can significantly impair the mechanical performance and long-term durability of load-bearing components since it occurs gradually and

is difficult to detect. According to earlier studies, intrinsic material flaws, residual welding stresses, and stress concentrations at crucial structural details are frequently associated with early-stage fatigue degradation. Continuous cyclic loading causes the steel to undergo microstructural evolution, which includes the creation of tiny fractures and dislocation structures [5]. These cracks often manifest as shear bands along grain boundaries or at interfaces of strengthening phases (Fig. 1). These alterations encourage the development of fatigue damage as well as its progression. The chance of structural collapse increases when damage reaches a critical level because it drastically affects ductility, load-carrying capacity, and resistance to fracture propagation.

It is crucial to methodically review and integrate current research findings in order to fully comprehend how pre-fatigue damage impacts the mechanical properties and microstructural characteristics of HSS as well as to evaluate the performance and residual service life of steel structures that have sustained such damage. In order to lower the danger of premature failure due to accumulated pre-fatigue damage, this technique facilitates the development of efficient design strategies and structural measures. The mechanisms and development of fatigue damage in HSS during its early service period are first discussed in this review paper. The study then examines how pre-fatigue affects the degradation of mechanical properties, contrasts conventional fatigue with pre-fatigue damage, and describes their unique characteristics [6]. The evolution of key performance metrics, including as strength, ductility, and fatigue life, is also investigated. Lastly, a technique for evaluating the mechanical performance of HSS exposed to pre-fatigue damage is suggested.

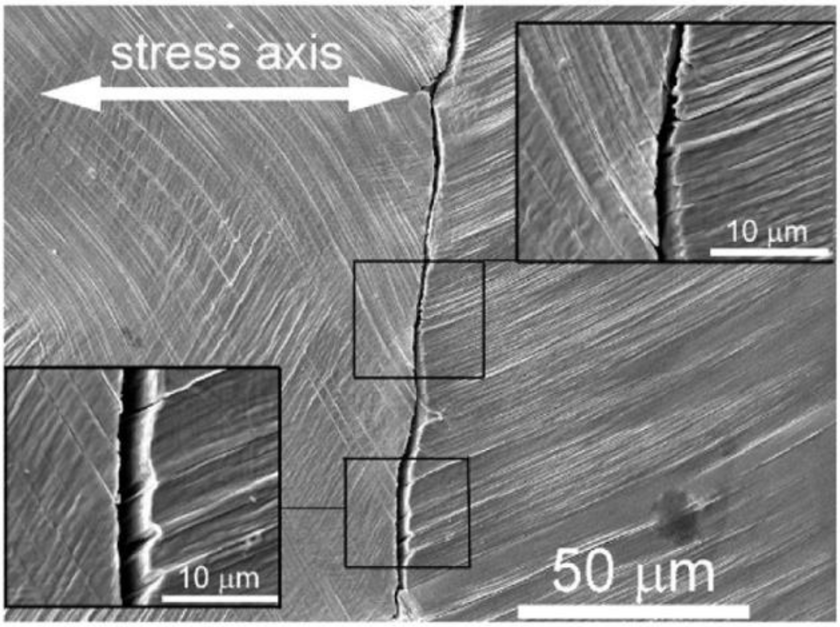


Fig. 1 Failure surfaces due to fatigue [7]

2. Structure of the Review Article

This reviews main strategies are divided into multiple sections. An overview of pre-fatigue damage in HSS is given in Section 3, along with an explanation of how it differs from conventional fatigue, how it develops, how it affects the microstructural behavior of the material, a description of common research techniques, and an assessment of the characteristics and applicability of commonly used damage assessment methods. From the perspectives of static, hysteresis, and fatigue properties, Section 4 examines how pre-fatigue affects the mechanical behavior and damage mechanisms of HSS while also identifying the shortcomings and gaps in present research. Methods for assessing pre-fatigue damage in HSS are presented in Section 5, together with an explanation of the features and suitability of several detection methods. Finally, Section 6 reviews the current understanding of HSS mechanical performance after pre-fatigue damage, identifies existing challenges, and suggests potential directions for future research.

3. Mechanisms of Pre-Fatigue Damage and Research Approaches in HSS

The early deterioration of microstructural flaws in a material before to its principal cyclic loading is referred to as pre-fatigue damage. Such damage usually results from environmental factors, manufacturing impacts, or previous loading. In contrast, under repeated loading in service, typical fatigue damage gradually changes. Alongside developments in fracture mechanics, the idea of pre-fatigue evolved with the goal of regulating crack initiation and facilitating accurate study of crack growth behavior. Compared to traditional fatigue mechanisms, this early damage phase is essentially different.

HSS research has mostly looked at the whole fatigue lifespan, from the start of cyclic loading to the end of the fracture. The focus has been on the damage that builds up over the course of the life cycle. Pre-fatigue damage, on the other hand, is about the early, non-destructive buildup of small flaws, especially changes in the microstructure inside the material before cracks are visible. This phase in HSS is mainly linked to the formation of martensitic shear bands, a rise in dislocation density, and micro-slip bands. These changes can make fatigue cracks happen much faster during the next service, even though they don't cause failure right away[8].

Studies also show that the way HSS fractures grow and the life of cracks that start before fatigue are very different from what happens when the material is loaded normally. Because of this, estimates of fatigue life based only on traditional data may make the material seem more durable than it really is. This could put structural safety assessments at risk. To accurately gauge the remaining service life and develop effective inspection and maintenance protocols, it is essential to understand and define pre-fatigue damage in HSS. In the end, this will make sure that steel structures can be used safely.

4. Effects of Pre-Fatigue on the Mechanical Properties of HSS

As the number of fatigue cycles goes up, tiny cracks start to form in the steel and slowly get bigger. The number of lattice flaws and dislocation density also goes up. This progression makes the material less hard and less flexible. At the same time, the appearance of residual stresses and changes has a big effect on how the microstructure behaves mechanically. Pre-fatigue damage makes HSS more likely to break because it lowers its yield and tensile strengths, ductility, and fracture toughness. The following is a summary of these effects:

i. The steel gradually develops microcracks and dislocations as the number of loading cycles increases, which lowers the steel's capacity for plastic deformation and deteriorates its ability to withstand strain. As seen in Fig. 8, the accumulation of fatigue damage reduces the effective load-bearing cross-sectional area, which causes a significant decline in both yield strength and tensile strength under tensile loading.

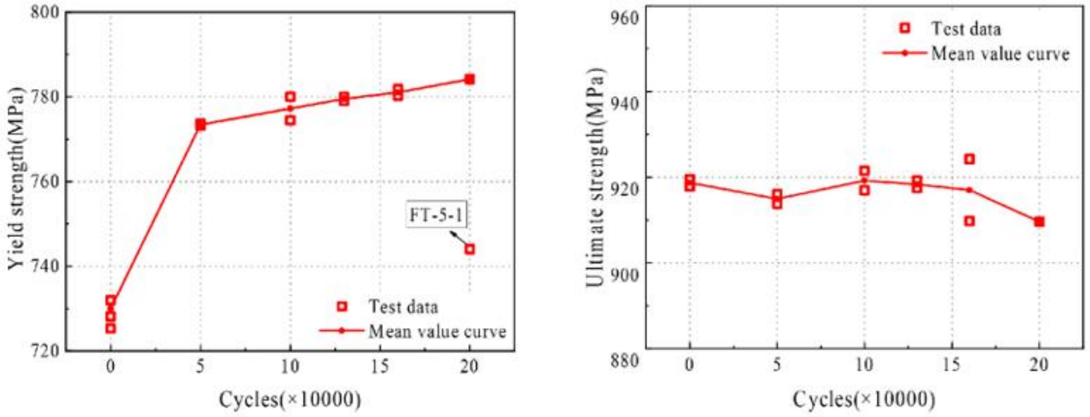
ii. Pre-fatigue damage to HSS increases the stress required for plastic deformation during future monotonic tensile testing due to an increase in dislocation density and their interactions, which improves the yield strength (Fig. 2(a)).

iii. Stress becomes more concentrated in specific areas with higher load amplitudes, hastening the development and expansion of microcracks. Additionally, increased loading increases the steel's plastic deformation zone, which results in higher residual stresses that hasten the spread of fatigue cracks and the accumulation of damage. Additionally, during static tensile tests, high-amplitude fatigue loading lowers fracture toughness and leads the material to reach its yield point early (Fig. 3), which ultimately results in a considerable loss in tensile characteristics.

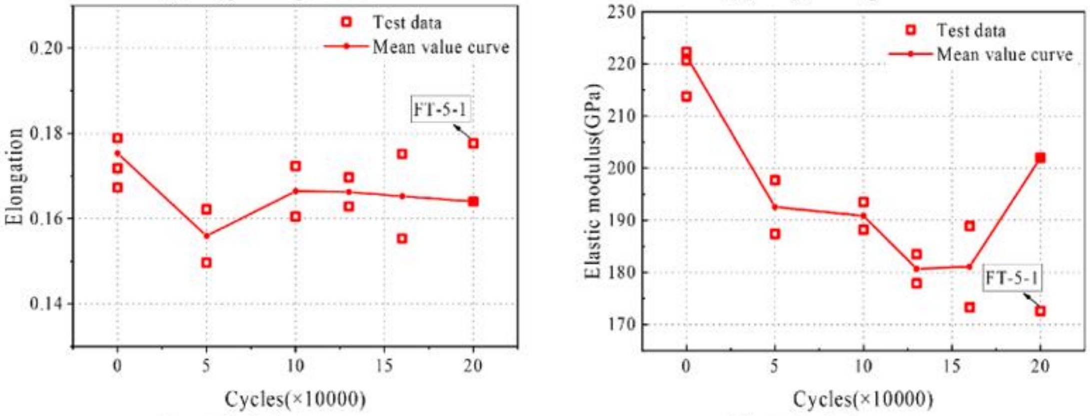
iv. Fatigue damage and its impact on static performance are significantly influenced by the microstructure of HSS. The way that pre-fatigue damage modifies tensile characteristics is directly impacted by changes in phase proportions and the distribution of precipitate strengthening phases, which also affect dislocation movement and crack propagation.

v. While compressive stresses can aid in slowing down crack propagation, residual tensile stresses typically increase crack formation while decreasing yield strength and fracture toughness.

vi. Pre-fatigue damage is significantly influenced by external factors as temperature, humidity, and corrosive surroundings. Such environmentally caused degradation can drastically lower steel's strength and ductility when it is subjected to tensile stress, ultimately reducing its static tensile behaviour.



(a) N-f_y fitting curve (b) N-f_u fitting curve



(c) N-δ fitting curve (d) N-E_s fitting curve

Fig.2 Mechanical properties of high-strength steel Vs number of pre-fatigue cycles[7]

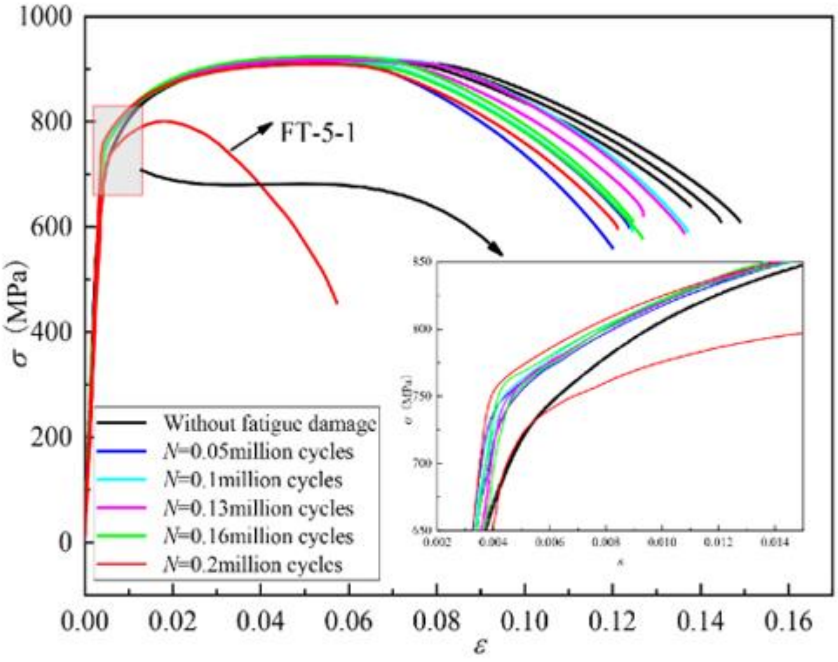


Fig. 3 Stress-strain curve for pre-fatigue damage of high-strength steel

5. Assessment of HSS Mechanical Properties after Pre-Fatigue Damage

In real-world situations, high-strength steel (HSS) experiences pre-fatigue degradation, which slowly weakens its mechanical properties and shortens its fatigue life, putting safety at risk. So, it's very important to accurately assess how pre-fatigue damage affects the mechanical behavior of HSS in order to make sure that steel structures are safe and reliable for a long time. Conventional mechanical testing methods can identify macroscopic property changes; however, they generally fail to detect the early-stage microscopic evolution of fatigue damage. To evaluate the mechanical performance of HSS post pre-fatigue damage, the following methodology is proposed:

i. Non-destructive testing (NDT) is very important for finding damage in HSS before it gets too bad. X-ray diffraction, magnetic particle testing, eddy current testing, and ultrasonic examination are some of the methods that can accurately find internal and surface flaws like cracks and areas that are affected by fatigue. These methods let you keep an eye on the damage as it gets worse without hurting the specimen. They also help you guess how big and how fast the fracture is growing and how much longer the material will last. Regular inspections let you keep an eye on the health of the structure in real time, which makes it safer overall and helps you plan maintenance more effectively [9].

ii. Microscopic inspection techniques elucidate the alterations in the internal structure of HSS caused by pre-fatigue damage. As fatigue progresses, micro cracks form, dislocation density increases, and phase composition and grain structure change. These small changes have a big effect on how things work mechanically. Studying the microstructure helps us understand how changes in macroscopic properties happen, how damage spreads, and how to improve materials and estimate their fatigue life.

iii. Using damage mechanics models and finite element simulations to pre-fatigue conditions can help make better predictions about how stress will spread and how fractures will form in HSS under complicated loading scenarios. Continuum damage mechanics and fracture mechanics models are two examples of methods that help with structural evaluation and maintenance plans. These models show how damage progresses and how much life is left in a structure. Also, numerical simulations make evaluations faster and more accurate, which leads to better structural design.

iv. Pre-fatigue damage in HSS often leads to the creation of complex residual stress fields, which greatly influence fatigue performance and mechanical features. These stresses can be measured and localized stress distributions can be found using methods like neutron diffraction, hole-drilling techniques, and X-ray diffraction. Fatigue life can be shortened by residual stresses, which can encourage crack initiation and quicken their propagation [10]. A thorough grasp of the material's internal state and safety performance can be obtained by analyzing these stresses in conjunction with other assessment techniques.

6. Conclusions and Future Scope

This paper examines the current understanding of the effects of pre-fatigue damage on the mechanical properties of high-strength steel (HSS). It examines the distinctions and correlations between pre-fatigue and traditional fatigue, elucidates the application of pre-fatigue loading and essential safety protocols, and investigates the fundamental micro-damage mechanisms in HSS subjected to pre-fatigue. It also looks at how this kind of damage affects mechanical performance from three different angles: resistance to fatigue, hysteretic response, and static tensile behavior. Based on this, a methodology for assessing the mechanical characteristics of HSS following pre-fatigue damage is put out, yielding the following findings:

i. Conventional fatigue encompasses the entire process from crack initiation through growth to ultimate failure, whereas pre-fatigue explains the accumulation of micro-level damage before to a crack forming. Both fatigue life and failure behavior are impacted by the microstructural alterations that take place during pre-fatigue, which produce the initial damage condition that propels subsequent crack formation. Pre-fatigue must therefore be included in order to create precise fatigue life models for HSS.

ii. During the earliest phases of service, HSS is subjected to complex cyclic loads that cause irreversible micro-level pre-fatigue damage, considerably influencing its later mechanical behavior.

iii. Pre-fatigue testing is essential for understanding the various scales at which damage manifests in HSS. By replicating the initial phases of service-induced degradation, it facilitates an in-depth examination of microcrack development, dislocation dynamics, and interfacial damage.

iv. Pre-fatigue damage has a big effect on HSS's static tensile properties, hysteretic response, and fatigue life. This leads to less strength, less stiffness, cracks starting earlier, and less fatigue durability.

v. To properly study how HSS behaves mechanically after pre-fatigue damage, advanced diagnostic methods should be used to fully capture how damage changes over time and how it affects material performance.

To get through these limits, future research should look into a number of important areas. To develop precise and reliable models for predicting material behavior, greater emphasis should be placed on integrating high-throughput experimental methodologies with artificial intelligence and machine learning. This method can help with quick evaluations and a better understanding of the processes that cause pre-fatigue damage. To be more specific, this includes the following parts:

- Create a comprehensive experimental database that encompasses data from various sources, including mechanical behavior, acoustic emission, digital image correlation, and microstructural characterization, obtained during the pre-fatigue loading phase.
- Use machine learning to find early-stage damage features and then use them to figure out a quantitative relationship between pre-fatigue signs and the remaining fatigue life.
- Make models based on data that can tell the difference between pre-fatigue damage and regular fatigue damage in complicated loading situations.

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