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# Behaviour of retrofitted steel structures using cost effective retrofitting techniques

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ABSTRACT

Steel structures today are edging towards the end of their design life. Recently, the frequency and magnitude of loadings are becoming significantly greater in comparison to the initial design loads at the time of construction. Deterioration from prolonged exposure to environmental conditions including weathering and climate change, as well as the effects of human error, also influence the design life of these older steel structures. The research focuses on developing a comparison between the fatigue performance of 120 years old and new equivalent steel structures. The fatigue resistance of both the old riveted and new welded steel structures is evaluated by investigating and analysing the stresses at critical locations within the structures. Retrofitting techniques are applied to both the old and new structures and analyzed in terms of their capacity to increase resistance to fatigue failure and extend the design life of steel structures. The research is conducted by performing both experimental study and finite element analysis. The experimental research analyses the performance of an old riveted structure, as well as a new equivalent prefabricated hot rolled section, to determine areas which are highly susceptible to fatigue failure. The numerical analysis using the finite element package ABAQUS is conducted to model both the old and new girder. Retrofitting proposals are introduced into the FE model both with and without the fatigue induced cracking to investigate improvements in the fatigue performance of the old and new girders, as well as techniques of repairing existing damage. The retrofitting techniques are cost effective and practical in engineering today to improve the performance and loading capacities to enhance the design life of steel structures. The retrofitting techniques are innovative, cost effective and practical in engineering today to improve the performance and loading capacities to enhance the design life of steel structures. An overall conclusion determines the extent of increasing design life, enhancing profitable engineering and focus on sustainability, in comparative terms of either retrofitting an old structure or replacing it with a new steel structure.

## 1. Introduction

During the late 19th and early 20th centuries, riveted steel construction increased in popularity as a result of rapid development of the transport system. Further developments and reliance on transport, increased the frequency of loading and effects of fatigue on these structures [1]. These riveted structures typically have a design life of 100 years, and are therefore reaching the end of this period and becoming more susceptible to fatigue based failure. Kuhn et al. [1] also identified the popularity of repair and strengthening of these types of structures in order to prevent fatigue failure and extend the design life of the structures. Riveted steel structures maintained their popularity until the middle part of the 20th century, when pre-fabricated steel structures such as welded and hot rolled sections became the dominant product for use in the steel construction industry. Even in today's society, pre-fabricated steel structures are still the preferred choice of steel product for engineers and designers. These types of structures have not been around long enough to come close to the 100 year design life, however it has been identified that fatigue based damage is occurring to these types of steel structures [1]. Due to technological developments and advancements in engineering knowledge, it can be shown that older bridges are subjected to increased loading conditions in comparison to the initial design loads. Steel bridges today are subjected to much larger magnitude and frequency of loadings compared to those at the time of construction [2].

Fatigue is a key failure component for steel structures that determines the structural performance. Repetitive application of various loadings can cause fatigue damage to continuously accumulate even though the loads may be well below the structural capacity of the steel structure. Understanding the effects of fatigue based damage with particular focus on steel structures such as steel bridges, has become more important as a result of increased magnitude and

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frequency of loadings due to population increases and reliance on and development of transport infrastructure. Sustained increases in fatigue damage (cracking) may lead to progressive failure of the structure [3]. Fatigue is complex and not precisely modelled due to the multitude of factors which control the response to cyclic loading. Therefore, experimental testing and finite element analysis is generally conducted to evaluate the fatigue behaviour of the structural members [4].

Rasidi et al. [5] classified fatigue failure into two types, low cycle fatigue and high cycle fatigue, dependant on the magnitude of the stress/strain and the number of cycles of the loading. Low cycle fatigue failure occurs when the structure fails after minimal cycles (a few cycles up to a few tens of thousands of cycles) under a large loading. High cycle fatigue failure occurs when the structure fails after a much greater number (several million) of cycles. The fatigue behaviour and failure of a structural element is dependent on a number of factors including the magnitude of the stress, material properties, temperature, surface finishing and the presence of any defects. Rasidi et al. [5] identified two key examples of defects which would indicate the presence of fatigue failure, a plate element with a hole and a notched plate. These two defects are associated with areas of higher stress/strain, therefore the cyclic loading will cause minute cracking to develop and become larger with each cycle, eventually leading to rupture of the steel section. Fig. 1 shows the fatigue cracking due to a plate element with a hole and a notched plate.

A typical example of fatigue cracking due to a plate element with a hole is shown in Fig. 2. Fig. 2 shows a small fatigue crack near the hole, which over time has propagated along the direction of the arrows over a larger portion of the section.

The most common approach to the visual representation and analysis of a fatigue assessment is to plot an S-N curve, where the total cyclic stress (S) is plotted on the y axis, against the number of cycles to failure (N) on a logarithmic scale on the x-axis. Rasidi et al. [5] recognised that an increase in the stress range of the cyclic loading will reduce the fatigue life of the steel structure. A typical S-N curve is shown in Fig. 3. The point at which the S-N curve flattens off is the fatigue limit. Ideally, if the applied loading is in the range of stress below the fatigue limit, the steel element should never be susceptible to fatigue failure. However, in the real situation, bridges are exposed to various condition which caused fatigue failure, therefore this research herein is looking at the fatigue behaviour of retrofitted steel structures using cost effective materials.

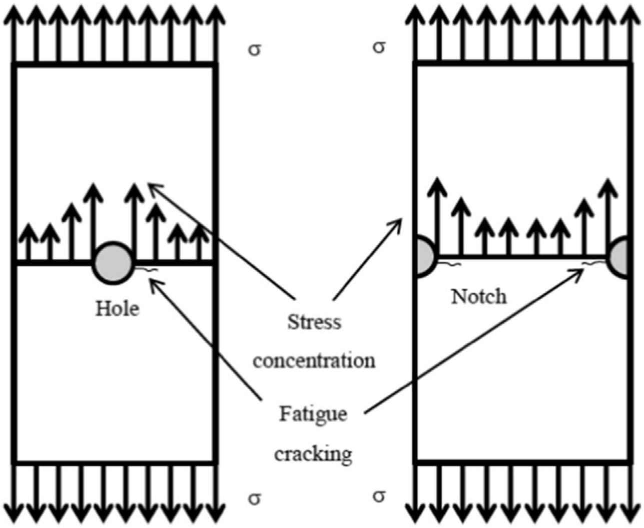

**Fig. 1.** Fatigue cracking due to stress concentration in plate with a hole and notched plate. (Rasidi et al. [5].)

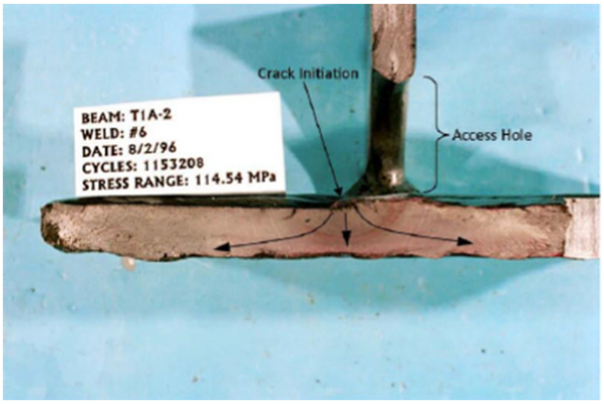

**Fig. 2.** Typical fatigue cracking due to plate with a hole. (Dexter & Ocel [10].)

## 2. Experimental program

Static strength tests were conducted on both the new and old girders in the Western Sydney University (WSU) laboratory. Both girders were simply supported with loading at the mid-span. Both girders were preloaded to 100 kN, and the load removed in three cycles before being loaded until failure.

### 2.1. Installation and test setup

All girders are 6477 mm in length, with stiffening plates as per Fig. 4 (Girder diagram showing dimensions, locations of stiffeners, loading and support system), with the dimensions as shown in Fig. 5. The test included the use of the following equipment:

1. 100-t hydraulic press to apply point load at the mid-span of the girders.
2. Roller support systems at each end of the girders.
3. Single and strip strain gauges to measure and record the stresses at the most critical locations within the girders.
4. Linear Variable Displacement Transducers (LVDT) to measure and record the deflection data for the girders under load.

The ultimate strength test (static load test) was carried out until failure on one of each of the provided old rivet and new welded steel girders (Table 1).

### 2.2. Static strength capacities

The Australian Standard for Steel Structures, AS4100-2012 (SAI [11]) was used to determine the shear capacity, moment capacity and ultimate applied load capacity of the old and new girders. Theoretically, the 120 year old RMS girder should fail following the application of a 583 kN point load is applied at the mid-span, while to new equivalent girder should fail following the applied load reaching 690 kN. The static

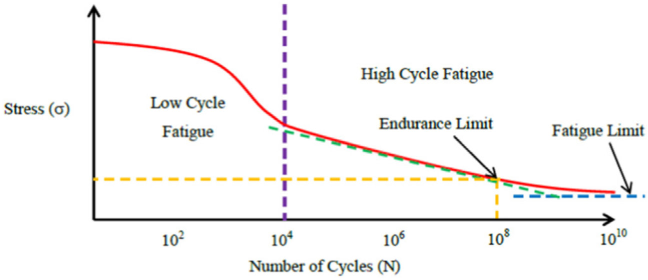

**Fig. 3.** Typical S-N curve showing low cycle and high cycle fatigue and endurance.