

Full paper

High-cycle fatigue performance of fillet welds in bridges

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Abstract

Fatigue performance of welded joints is a critical consideration in the design, assessment, and maintenance of steel railway bridges, particularly under high-cycle loading conditions imposed by repeated train passages. In New Zealand, fillet welds are encouraged to be used in bridge components due to their simplicity of fabrication, reduced construction time, and cost-effectiveness; however, these welds are generally regarded as being more susceptible to fatigue cracking because of geometric discontinuities and stress concentrations at the weld toe and root. As KiwiRail advances its national infrastructure upgrade and bridge standardisation programmes, a reliable and quantitative evaluation of the fatigue behaviour of welded details is essential to ensure adequate durability, structural reliability, and safe service life.

This study is about experimental investigation into the high-cycle fatigue performance of fillet-welded T-joint specimens representing typical welded details used in New Zealand steel railway bridges, including flange-to-web and stiffener-type connections. The specimens are being fabricated from G350 structural steel using local welding procedures and are to be tested under sinusoidal cyclic loading using a 250 kN servo-hydraulic MTS dynamic actuator in a purpose-designed test rig. The loading parameters, including stress range and frequency, are selected to simulate realistic service conditions while satisfying high-cycle fatigue testing requirements. Strain gauges, LVDTs, and visual monitoring are to be employed to record structural response, crack initiation, and crack propagation behaviour. The results will provide experimental S-N data and will be used to support and assess structural stress-based fatigue evaluation methods for future application in bridge design and assessment.

Keywords

High-Cycle fatigue, fillet weld, bridge, Fatigue failure, S-N curve

1 Introduction

Steel railway bridges form a vital part of transportation infrastructure worldwide and are required to provide safe and reliable service over long operational lifetimes under repetitive traffic loading. In many existing and newly constructed bridges, particularly those based on steel plate girder (SPG) systems, welded connections are extensively used to connect flanges, webs, and stiffeners. Among the various welded details, fillet welds are encouraged to be widely adopted in New Zealand, instead of full penetration butt welds (FPBW), due to their simple fabrication, reduced construction time, and cost-effectiveness compared with FPBW. Despite these practical advantages, fillet welds are often considered to be more vulnerable to fatigue damage because of their inherent geometric discontinuities and the associated stress concentrations at the weld toe and weld root [1,2].

Fatigue has long been recognised as one of the governing limit states in the design and assessment of steel bridges, especially for railway structures that are subjected to a very large number of load cycles generated by passing trains. Even when the nominal stress ranges remain well below the yield strength of the material, the accumulation of cyclic damage can lead to crack initiation and subsequent propagation, potentially resulting in brittle fracture if not detected and mitigated in time [1]. Field observations and historical experience consistently show that welded details represent some of the most fatigue-critical aspects in steel bridges, with cracks frequently initiating at weld toes, weld roots, or other local geometric discontinuities [1,3,4].

In New Zealand, KiwiRail is currently undertaking a long-term programme to upgrade, renew, and standardise its bridge infrastructure, with a strong emphasis on improving constructability, durability, and life-cycle cost efficiency.

Within this context, fillet welds are frequently preferred in structural details such as flange-to-web connections and stiffener attachments in new KiwiRail steel bridges. However, the fatigue performance of these details under high-cycle loading conditions representative of in-service railway traffic requires careful and quantitative assessment to ensure that adequate safety margins and service lives are achieved. While existing design standards [2] provide fatigue classifications for a wide range of welded details, these classifications are often conservative and may not fully reflect the actual performance of specific weld geometries, fabrication practices, and material grades used in New Zealand bridge construction.

Furthermore, the increasing age of the bridge stock, combined with rising traffic volumes and axle loads, has heightened the importance of reliable fatigue assessment methods for both new and existing welded bridge structures. In this context, there is a need for experimental data obtained from representative welded details fabricated using local materials and welding standards including AS/NZS1554, to support rational fatigue design and assessment and to reduce unnecessary conservatism where appropriate without compromising safety.

The present study addresses this need by proposing a systematic experimental investigation into the high-cycle fatigue performance of fillet-welded T-joint specimens representative of typical welded details in steel railway bridges, including flange-to-web and stiffener-type connections. 25 specimens are considered to be tested but 13 specimens are being fabricated from G350 structural steel using local welding practices as a first phase and are tested under controlled sinusoidal cyclic loading conditions using a servo-hydraulic testing system. The experimental programme is intended to generate reliable fatigue data in the high-cycle regime, including S–N relationships and observations of crack initiation and failure modes.

In addition to providing experimental evidence, the results of this study will be used to support the evaluation of structural stress-based fatigue assessment methods for application in bridge engineering practice. The overall objective is to establish a robust experimental basis for assessing the fatigue performance of fillet welds in bridge applications and to contribute to the development of more rational and reliable fatigue design guidance for welded railway bridge structures.

2 Background and Literature Review

2.1 Fatigue in Steel Bridges

Historical railway accidents and numerous in-service observations have demonstrated that fatigue failure can occur in welded structures after long periods of use, highlighting the insidious nature of this damage mechanism [1].

Wöhler's pioneering work on fatigue established the relationship between stress range and number of cycles to failure, leading to the well-known S–N concept that still forms the basis of most fatigue design approaches [1]. In bridge engineering practice, fatigue is particularly critical because structures are exposed to millions of load cycles during their service life, and because inspection and repair of fatigue cracks can be costly and disruptive to operation. Welded details are widely recognised as the most fatigue-sensitive parts of steel bridges due to the combined effects

of geometric discontinuities, residual stresses, and welding-induced imperfections [1,3].

In railway bridges, fatigue demand is further intensified by increasing axle loads, higher traffic volumes, and, in some cases, higher train speeds [5]. Consequently, fatigue has become a dominant consideration not only for the design of new bridges but also for the assessment and remaining life estimation of existing bridges. Many documented fatigue problems in steel bridges originate at welded details such as stiffener terminations, flange-to-web connections, and attachments to primary members, where local stress concentrations govern fatigue crack initiation [4].

2.2 Fatigue Behaviour of Fillet Welded Joints

Fillet welds are among the most commonly used welded joint types in steel bridge construction due to their simple fabrication, adaptability to a wide range of joint configurations, and cost-effectiveness compared with partial or full penetration butt welds. Despite these practical advantages, fillet welds are inherently associated with stress concentration effects at both the weld toe and the weld root, making them particularly susceptible to fatigue cracking under cyclic loading [1].

Experimental observations and field experience show that fatigue cracks in fillet-welded joints most frequently initiate at the weld toe, where the combined effects of geometric notch, residual stresses, and local stress gradients are most severe [1,2]. In some cases, especially for partial penetration or poorly executed welds, crack initiation may also occur at the weld root [1,2,4]. The fatigue behaviour of fillet welds is influenced by many factors, including weld profile, plate thickness, joint geometry, material properties, residual stresses, and welding defects such as undercut, lack of penetration, or porosity [1,3,4].

In the high-cycle fatigue regime, which is characterised by fatigue lives typically exceeding 10^5 – 10^6 cycles, the structural response generally remains elastic, and fatigue life is dominated by crack initiation and early crack growth [6]. For this reason, the local stress field at the weld toe plays a decisive role in governing fatigue performance. Studies on welded bridge details have shown that even relatively small changes in weld geometry or local stress concentration can lead to significant differences in fatigue life [4].

Recent investigations have also highlighted the role of residual stresses in fillet-welded joints. Sonsino [3] showed that residual stresses can significantly influence fatigue behaviour, particularly in the high-cycle regime, although their effect tends to diminish in the finite-life range due to local plasticity.

2.3 Fatigue Assessment Approaches for Welded Joints

Several approaches are available for the fatigue assessment of welded joints, and their applicability depends on the complexity of the joint geometry and the level of detail required [2]. International design recommendations, such as those issued by the International Institute of Welding (IIW), classify welded details into fatigue categories and provide corresponding S–N curves based on nominal stress ranges [2,5].

To address these limitations, local stress-based methods have been developed, including the structural hot-spot stress method and the effective notch stress method [5,6]. These approaches aim to capture the local stress field at fatigue-critical locations, particularly at the weld toe, and have been shown to provide a more consistent treatment of geometrical effects.

Among these, the structural stress method proposed by Dong [7,8] has attracted significant attention because it provides a mesh-insensitive and mechanics-based definition of stress that separates membrane and bending components, and correlates well with fatigue test data for a wide range of welded joints. This method has been successfully applied in offshore, marine, and bridge structures and offers a promising framework for evaluating fatigue performance of fillet-welded joints with complex geometries.

Niemi [6] and Maddox [1] provide comprehensive discussions on the determination of stresses for fatigue analysis of welded components and the practical implementation of local stress-based approaches. These methods are particularly attractive for bridge applications, where welded details often exhibit complex stress distributions that cannot be adequately represented by nominal stresses alone.

In the context of the present study, a structural stress-based approach is considered especially suitable for interpreting the experimental results obtained from fillet-welded T-joint specimens. By relating the measured or calculated structural stress at the weld toe to the observed fatigue life, the study aims to contribute to a more rational and transferable fatigue assessment framework for fillet welds in steel bridge structures.

3 Scope and Objectives of the Study

The present study is focused on the high-cycle fatigue performance of fillet-welded joints representative of typical welded details used in steel railway bridges in New Zealand. The scope is intentionally limited to fillet-welded T-joint configurations that simulate common structural applications such as flange-to-web and stiffener-type connections in steel plate girder bridges. Other joint types, such as partial or full penetration butt welds, are outside the scope of this investigation at this stage.

The study concentrates on the high-cycle fatigue regime, in which the structural response remains predominantly elastic, and fatigue lives are governed by crack initiation and early crack growth from stress concentration sites, particularly at the weld toe. Low-cycle fatigue behaviour associated with seismic or extreme loading events is not considered in this stage of this work.

The experimental programme is designed to generate reliable fatigue data from specimens fabricated using G350 structural steel and local New Zealand welding practices, in order to ensure that the results are representative of actual bridge construction conditions. The tests are conducted under controlled, force-controlled sinusoidal cyclic loading intended to simulate service-type loading conditions experienced by welded bridge components.

In addition to generating experimental S-N data, the study aims to provide a basis for evaluating structural stress-based fatigue assessment methods for fillet-welded joints. By relating experimentally observed fatigue lives to the local stress state at the weld toe, the study seeks to assess the suitability of such methods for application in bridge engineering practice.

4 Experimental Programme

4.1 Specimen Design and fabrication

The specimen configuration is widely adopted in fatigue research on welded joints because it reproduces the essential geometric features and stress concentration characteristics governing fatigue crack initiation at the weld toe [9,10].

Each specimen consists of a stem plate welded to a base plate using double-sided fillet welds. The specimen dimensions are selected to satisfy several requirements: (1) to achieve the target stress level at the weld toe under laboratory loading, (2) to be representative of plate thicknesses commonly used in bridge components, (3) to remain within the load and displacement capacity of the testing equipment, and (4) to minimise unintended secondary stress concentration effects away from the weld region. The weld geometry is also chosen such that fatigue cracking is expected to initiate at the weld toe on the base plate side, which is the intended fatigue-critical location and align with New Zealand standards.

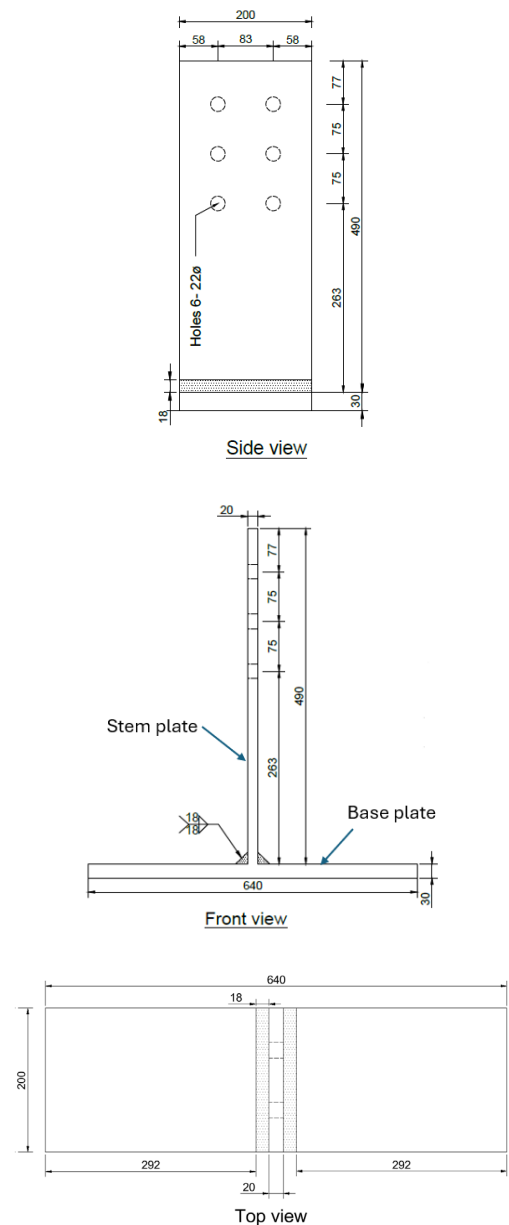


Figure 1 Test Specimen Dimensions and views

4.2

All specimens are fabricated from G350 structural steel, which is widely used in New Zealand bridge construction. The nominal yield strength of this steel grade is 350 MPa. The use of G350 steel ensures that the test results are directly relevant to current bridge engineering practice in New Zealand. The welding method is Submerged Arc Welder (SAW) according to AS/NZS1554.

The fatigue tests are designed such that the stress range in the specimens remains within the elastic range of the material, thereby ensuring that the experiments are conducted in the high-cycle fatigue regime. The elastic material behaviour assumption is also consistent with the use of stress-based fatigue assessment methods and S-N curve interpretation.

4.3

The specimens are welded using local New Zealand industry practices and standards to ensure that they are representative of real bridge fabrication conditions. Double-sided 18mm fillet welds are applied along the junction between the stem and base plates. Care is taken to achieve consistent weld size, profile, and quality across all specimens.

Prior to testing, all welds are visually inspected to ensure acceptable surface quality and uniformity of weld geometry. Particular attention is paid to avoiding excessive undercut, irregular weld profile, or visible surface defects that could introduce unintended variability in fatigue performance. In addition, etching tests are conducted on all welds to reveal a weld's internal cross-section, including penetration depth and heat-affected zones and the specimen dimensions are measured using a 3D scanning machine. The objective is not to produce "perfect" laboratory welds, but rather to reproduce realistic fabrication quality consistent with practical bridge construction.

4.4 Test Setup and Loading System

The fatigue tests are performed using a servo-hydraulic 250kN MTS dynamic actuator (figure 2) and associated control system. This includes a 244.31G2 250 kN (55 kip-force) actuator, 793/TestSuite-Multi Purpose (MP) software, and Flex Test 40 Controller. The actuator is mounted vertically within a designed reaction frame, including two columns and a short beam used to form the reaction frame. The actuator is to be used vertically, with one end of the actuator bolted to the short beam and the other end connected to the red pedestal which is bolted to the clamping angles (figure 3 and 4). The test specimen's stem is mounted to clamping angles with 6xM20 bolts (figure 4), and the specimen's base is mounted with four round plates on either side to simulate a simple support connection (figure 5).

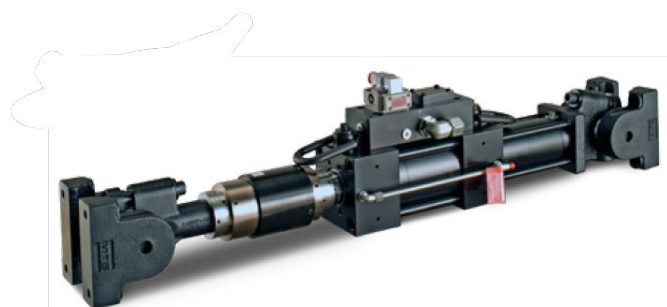


Figure 2 250kN MTS servo-hydraulic dynamic actuator (From manufacturer catalogue)

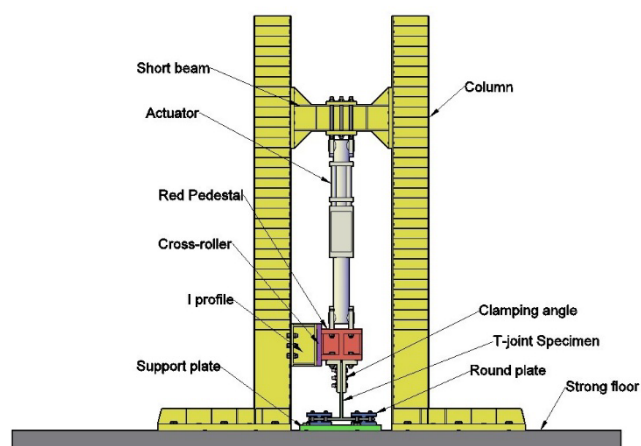


Figure 3 Overview of the test setup

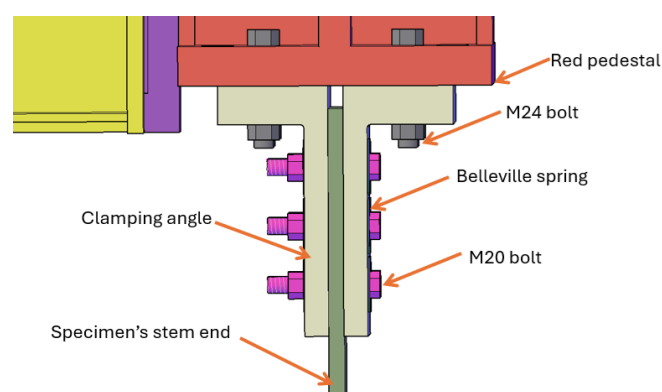


Figure 4 Bolted connections at the stem end

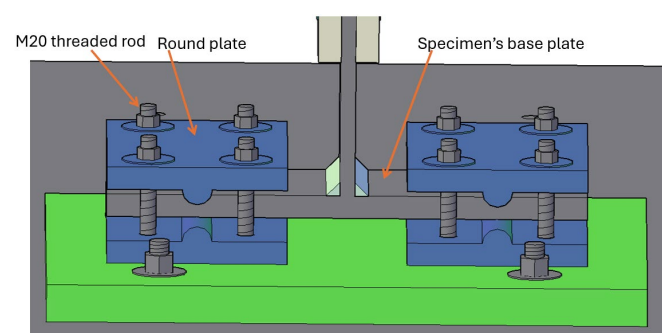


Figure 5 Simulating a simple support connection on either side of base plate

The stem of the specimen is clamped using high-strength bolted connections, while the base plate is supported using a bolted support system that replicates simple support conditions. This configuration ensures stable load transfer in a simply supported bending form.

To prevent out-of-plane movement and eliminate longitudinal friction during testing, a cross-roller guiding system (figure 6) is to be employed to laterally restrain the red pedestal/actuator while allowing essentially frictionless vertical motion (figure 7). The overall setup is designed such that the applied force produces a dominant bending stress, σ_2 , at the weld toe located at the base plate side of the T-joint, which is the intended fatigue-critical location (figure 8).

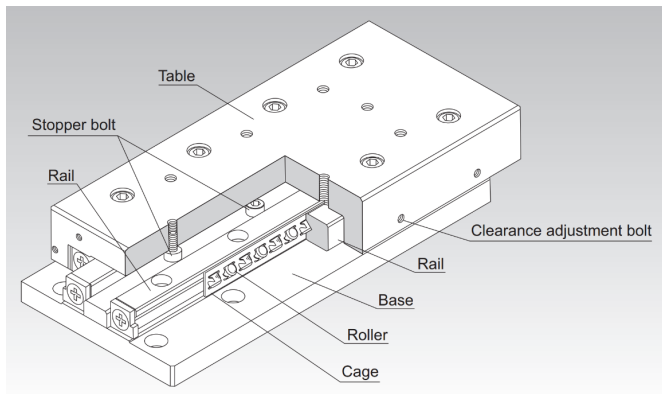


Figure 6 Cross-roller guide

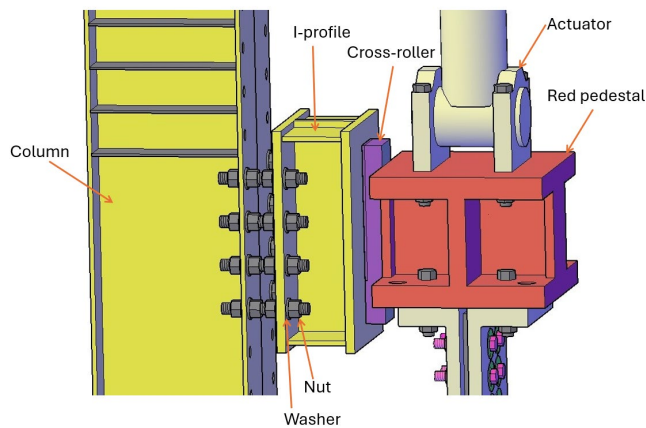


Figure 7 Cross-roller location

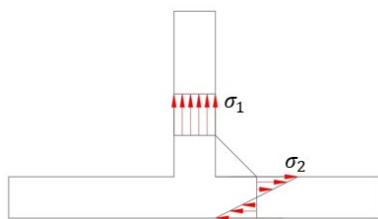


Figure 8 Stress indication at weld toes

All components of the test setup are designed to remain elastic under the maximum possible actuator load, and fatigue checks are carried out to ensure that no part of the rig becomes the governing fatigue-critical component during the tests.

4.5 Instrumentation and Data Acquisition

Strain gauges are installed near the weld toe on either side of both the stem and base plates in order to measure local and global strain responses (figure 9). The gauge layout is designed to capture the stress distribution in the vicinity of the fatigue-critical region and to allow verification of the applied stress range at the weld toe. Strain gauges model is FLAB-6-350-11-3LJC-F, with 5mm single element length and 350Ω resistance suitable for high-cycle fatigue test. The measured strains are converted to stresses using Hooke's law, assuming linear-elastic material behaviour.

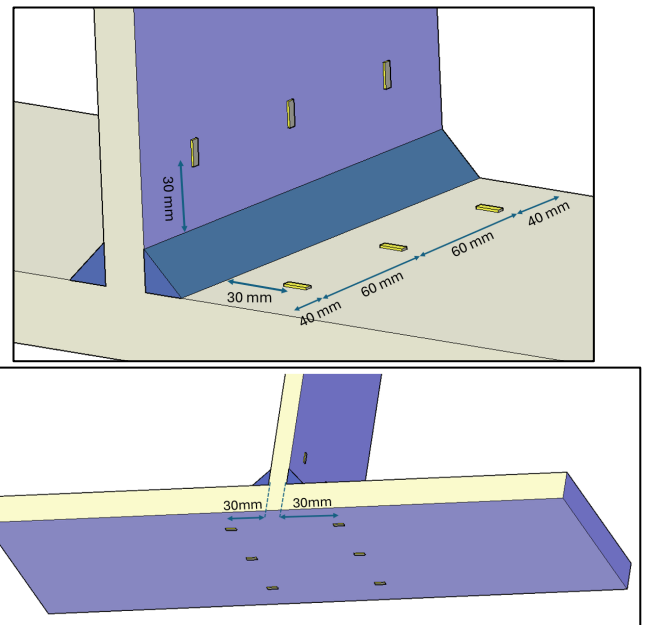


Figure 9 Strain gauges locations (Either side of stem plate, Top face and bottom face of base plate)

Displacements are measured using both the internal LVDT of the hydraulic actuator and two external LVDTs installed to measure relative displacements between the stem plate, base plate, and strong floor. These measurements allow verification of the intended deformation mode and identification of any unintended flexibility in the test setup.

The applied force is continuously monitored using the internal load cell of the actuator. In addition, accelerometers are installed on the loading pedestal to allow inertia effects to be quantified and, if necessary, removed from the measured force values recorded by the actuator. Visual monitoring using high-resolution cameras is employed to observe crack initiation and crack propagation during the tests. A Nikon D5000 camera and ELP-USB4K03-MFV (2.8-12) cameras will be positioned facing front views. This facilitates better interpretation of the data ensuring that no critical details are overlooked during the test.

All measurement signals are recorded using a synchronized National Instrument data acquisition system throughout the duration of each fatigue test.

4.6 Loading Protocol and Test Matrix

The fatigue tests are conducted under force-controlled cyclic loading using a sinusoidal waveform. A sinusoidal loading history is adopted because it provides a smooth, stable, and well-defined cyclic load pattern that is widely used in high-cycle fatigue testing and allows precise control of frequency and stress range [6].

The maximum stress level is selected as a fraction of the yield stress of G350 steel to ensure that the specimens remain in the elastic range throughout the tests. Several researchers typically select stress ranges between 120 and 320 MPa, factoring in the yield strength of the steel used in their tests, with a minimum stress set between 0–20% [4,6]. Considering the yield strength of G350 steel, the selected stress levels remain well within the elastic range ($\sigma_{\max} = 185 \text{ MPa} < f_y = 350 \text{ MPa}$), ensuring that cyclic loading is governed by high-cycle fatigue conditions rather

than cyclic plasticity. A minimum stress of 35 MPa (approximately 10% of the stress range) was adopted to maintain a stable tension-tension loading regime and to avoid unloading to near-zero stresses, which may introduce experimental instability and crack closure effects. This selection also helps ensure sufficient fatigue life to reach the target of 2×10^6 cycles without premature failure.

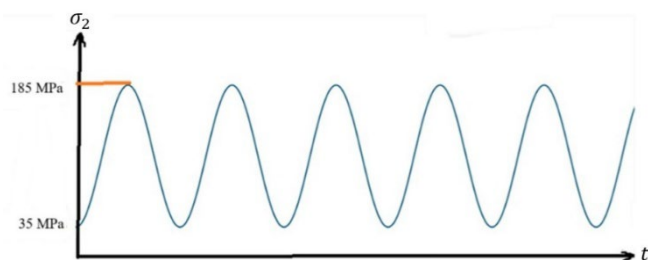


Figure 10 Loading regime graph

Each specimen is tested until a fatigue crack is detected and propagates to a predefined failure criterion or until a specified run-out limit is reached. The number of cycles to crack initiation and final failure, together with the applied stress range and observed failure mode, are recorded for subsequent fatigue analysis and S-N curve construction.

5 Planned Data Processing and Fatigue Evaluation Methodology

This section describes the methodology that will be used to process the experimental data and to evaluate the fatigue performance of the tested joints in a form suitable for engineering interpretation and comparison with established fatigue design approaches.

The primary outputs of the fatigue tests are the applied stress range, the number of cycles to crack initiation and/or failure, and the observed crack initiation location and failure mode. These data will be analysed using both conventional S-N curve concepts and local stress-based fatigue assessment approaches, with particular emphasis on structural stress and hot-spot stress methods. Furthermore, the obtained fatigue performance will be assessed in relation to the corresponding fatigue class to determine whether the investigated welded details exhibit conservative or non-conservative behaviour with respect to standard design curves.

5.1 S-N Curve Development

The S-N (stress-life) approach remains the most widely used method for fatigue design and assessment of welded joints in steel structures. In this approach, the relationship between the applied stress range, $\Delta\sigma$, and the number of cycles to failure, N , is expressed in the form of an S-N curve, typically plotted on a log-log scale [2].

For each tested specimen, the applied nominal or reference stress range and the corresponding number of cycles to crack initiation or final failure will be recorded. These data points will be used to construct experimental S-N curves for the tested fillet-welded T-joints. Specimens that do not fail upon reaching the predefined maximum cycle limit (2×10^6) will be classified as run-out specimens and

treated as right-censored data in the S-N regression analysis, in accordance with established fatigue testing practice [11,12].

The experimental S-N data will be compared with relevant fatigue classes recommended by international design guidelines, such as those provided by the International Institute of Welding (IIW) [2,5], in order to assess the conservatism or adequacy of existing fatigue classifications for the tested joint configuration. Although nominal stress-based S-N curves are simple and practical, their applicability is often limited by ambiguities in nominal stress definition for complex joint geometries [2,6,8]. For this reason, the S-N results will also be interpreted using local stress-based approaches, as described in the following subsection.

5.2 Structural Stress / Hot-Spot Stress Evaluation

To overcome the limitations of the nominal stress approach, local stress-based fatigue assessment methods will be employed to interpret the experimental results. These methods aim to characterise the stress state at the fatigue-critical location, typically the weld toe, in a manner that is less sensitive to joint geometry and mesh dependency.

The hot-spot stress method is based on extrapolation of surface stresses near the weld toe to obtain a structural stress that excludes the local notch effect of the weld profile. This approach has been widely adopted in fatigue design of welded joints and is recommended in several international guidelines.

In addition, the structural stress method proposed by Dong [8] provides a mechanics-based definition of stress that separates membrane and bending components and is formulated to be insensitive to finite element mesh density. This method has been shown to correlate well with fatigue test data for a wide range of welded joint configurations and offers a unified framework for fatigue assessment of welded structures.

In the present study, the structural stress (or hot-spot stress) at the weld toe will be determined based on the measured strain data and/or supplementary numerical analysis. The experimental fatigue lives will then be correlated with the corresponding structural stress ranges to evaluate the consistency of the results with existing master S-N curves proposed in the literature. This will allow an assessment of whether the tested fillet-welded bridge details conform to established fatigue design frameworks or exhibit systematic deviations that may justify refinement of current design assumptions.

5.3 Crack Initiation and Failure Mode Classification

In addition to fatigue life data, detailed observations of crack initiation location and failure mode will be used as an essential part of the fatigue performance assessment. Visual monitoring and post-test inspection will be employed to identify whether cracks initiate at the weld toe, weld root, or other locations, and to document the subsequent crack propagation path. Failure is defined in terms of a significant reduction in specimen strength against cy-

clic loads. During the crack initiation phase, strength degradation is not readily detectable, whereas it becomes increasingly evident during the crack propagation phase.

The distinction between weld toe failure and weld root failure is particularly important for fillet-welded joints, as it reflects different governing stress mechanisms and has direct implications for both design and inspection strategies. The observed failure modes will be classified and correlated with the applied stress range, joint geometry, and local stress state.

Where possible, the number of cycles to crack initiation will be distinguished from the number of cycles to final failure. This distinction provides insight into the relative contributions of crack initiation and crack propagation to the total fatigue life, especially in the high-cycle regime where crack initiation often dominates [12].

By combining S–N analysis, structural stress evaluation, and failure mode classification, the study aims to provide a comprehensive and mechanics-consistent interpretation of the fatigue behaviour of fillet-welded joints representative of bridge applications.

6 Expected Results and Discussion Framework

The experimental programme described in the previous sections is expected to generate a consistent and reliable set of high-cycle fatigue data for fillet-welded T-joint specimens representative of typical bridge details. It is anticipated that fatigue cracks will predominantly initiate at the weld toe on the base plate side of the specimens, where the local stress concentration is highest. The discussion will focus on comparing the experimentally obtained S–N data with existing fatigue classes recommended in international design guidelines, in order to assess the level of conservatism or adequacy of current fatigue design assumptions for fillet-welded bridge details fabricated using local practices. Particular attention will be given to whether the tested details fall consistently above or below the relevant design curves, and to the implications of this for practical bridge design and assessment.

In parallel, the results will be interpreted using structural stress and/or hot-spot stress concepts. The relationship between fatigue life and the corresponding structural stress range at the weld toe will be examined to assess the consistency of the results with existing master S–N curves proposed in the literature. This will provide a basis for evaluating the suitability of local stress-based approaches for fatigue assessment of fillet-welded bridge details and for identifying any systematic trends or deviations specific to the tested configuration and fabrication practice.

The observed crack initiation and propagation behaviour will also be discussed in relation to the applied stress level and joint geometry. Where possible, the relative contributions of crack initiation and crack growth to the total fatigue life will be assessed.

7 Implications for Bridge Design Practice

The outcomes of this study are expected to have direct relevance to the fatigue design and assessment of welded details in steel railway bridges, particularly in the context of bridge renewal and standardisation programmes in New

Zealand. By providing experimental fatigue data for fillet-welded joints fabricated using local materials and welding practices. The study will contribute to a more realistic and application-oriented understanding of the fatigue performance of these commonly used details.

In addition, the findings will support improved decision-making in the assessment and remaining life estimation of existing bridges by providing better guidance on the expected fatigue behaviour of critical welded details. The results may also inform fabrication and quality control practices by highlighting the importance of weld geometry and local stress concentration in governing fatigue performance.

Overall, the study aims to bridge the gap between generic design guidance and the actual performance of locally fabricated welded bridge details, thereby contributing to safer, more durable, and more economical steel bridge infrastructure.

8 Conclusions

This paper has presented the scope, motivation, and methodology of an experimental investigation into the high-cycle fatigue performance of fillet-welded joints representative of typical welded details in steel railway bridges. The study focuses on fillet-welded T-joint specimens fabricated from G350 structural steel using local New Zealand welding practices and tested under controlled cyclic loading conditions.

A comprehensive experimental programme has been described, including specimen design, material selection, welding procedure, test setup, instrumentation, and loading protocol. A structured methodology for data processing and fatigue evaluation has been proposed, combining conventional S–N curve analysis with local stress-based fatigue assessment approaches, including structural stress and hot-spot stress concepts. In addition, a framework for crack initiation and failure mode classification has been established.

It is worth noting that at the time of writing this paper, the specimens and setup components are being fabricated. However, at the time of presenting this paper at the conference, the results will be available and presented.

Acknowledgments

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