Negus R
Cardiff University
School of Engineering

Novelli V
Cardiff University
School of Engineering

Bertolesi E
Cardiff University
School of Engineering

Cashell K
University College London
Department of Civil, Environmental and Geomatic Engineering

COMPUTATIONAL MODELLING AND DIGITAL TWINS

Investigation into the Accumulated Fatigue Damage in Riveted Connections in Steel Bridges using Advanced Numerical Techniques

Fatigue in traditional riveted steel bridges is being observed at increasing frequency due to an increase in both the volume and mass of expected traffic. The financial ramifications of retrofitting, repairing and insuring bridges from this damage is vast, and many rail networks suffer from inadequate funding to address these issues. In the financial year 2019-2020 it was estimated that the cost of maintenance on the British rail network was £1.488 billion, and arguments for safety and sustainability can also be emphasised because of this form of damage. With comparable increases in volume and frequency of rail traffic, it is not inconceivable to see comparable damage occurring in contemporary infrastructure soon. This paper investigates the validity of using traditional numerical techniques to model a complex system of rivets and structural members, with the future aim of utilising the more advanced eXtended Finite Element Method (XFEM) to analyse the mechanism behind fatigue propagation in the riveted connections of steel rail bridges, addressing the effect of loading conditions and rivet geometry on crack nucleation, propagation, and failure.

Keywords:
Fatigue, rivet, FEA, FEM, XFEM.

Corresponding author:
NegusRP@cardiff.ac.uk

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INTRODUCTION

Most traditional rail bridges in the UK, Europe, and America were constructed from a system of riveted wrought-iron girders and perpendicular stringers over 100 years ago [1] [2]. The loading conditions on these structures has acutely increased in both frequency and magnitude since their initial construction, with demands from both freight and passengers rising. In recent years, it has been observed that these increasing loads have caused accelerated fatigue deterioration in the riveted sites, causing cracking and weakening of key intersections.

The primary focus of this project will look at the loading conditions for these bridges and use advanced numerical techniques to model the mechanism of fatigue nucleation occurring within the riveted points at the primary connection sites. These connections will be modelled in ABAQUS using the eXtended Finite Element Method (XFEM), with an emphasis on analysing the specific geometry of the rivet holes at the connection sites.

This paper presents the initial results from numerical modelling of static loading criteria of a complex system of rivets and structural elements that make up a crossbeam of the Quisi Bridge, constructed in Spain in 1915 (Fig. 1). Due to the non-standardised construction methods employed prior to 1940, unknown factors such as coefficient of friction, clamping force, and pre-stress effect are considered [3]. The approach is validated using strain gauge data from a crossbeam of the Quisi bridge subject from previous studies [4].

Fig 1. Location and view of the Quisi Bridge, the focus of this work.

MATERIALS AND METHODS

Fatigue

Fatigue is understood to occur through crack nucleation and propagation caused by cyclical loading at a point of localised high stress. At regions of high stress, localised plastic strain occurs in metal grains causing dislocations in atomic arrangement, allowing crystal planes to slide over one another (known as a slip plane). Crystal planes tend to be formed parallel to one another, and the shear stress of one slip plane moving drags others with it, resulting in “slip bands”. Continuous cyclic stresses cause these slip bands to slide back and forth, resulting in extrusions and intrusions at the grain boundary. These anomalies result in micro-crack nucleation (known as Stage I crack growth), and it is at these points where cracks begin. Micro-cracks will slowly propagate through a series of grains, until the micro-crack is large enough that a tensile plastic stress zone forms around the tip. Once the crack is large enough, the global tensile stresses dominate and force the crack to open, travelling perpendicular to this applied stress (known as Stage II crack growth). For this reason, tensile forces are far more dominant in fatigue performance of metals than compressive forces.

Fatigue can generally be characterised as high cycle fatigue (HCF), low cycle fatigue (LCF), or a combination of the two. LCF is characterised by micro0plastic damage in the stress cycle, typically greater than the endurance limit of the material (where cracks develop), coupled with low frequency [5][6]. LCF is also notably predominant in geometric features such as holes and sharp changes, such as notches, and as such, is the representative loading case in railway structures.

FEM and XFEM

The finite element method is a numerical tool that can be traced back to the 1940s when Hrennikoff proposed using a series of rods and beams to approximate a stress solution in continuous solids. Development of more sophisticated computers led to more complex matrices being solved, resulting in the advent of the stiffness matrix in the 1950s. For both implicit and explicit approaches in FEA, the analysis is ultimately aiming to solve a series of displacements arising from disturbances applied to the finite element mesh from a boundary-value problem. In either case, the solver will approximate a solution for the global displacement vector in three dimensions. The fundamental equations for solving for displacement using implicit and explicit solvers are given in Eq. 1 and Eq. 2. In Eq. 1, K and F represent the stiffness matrix and force vector, while in Eq. 2, N represents the individual node degree of freedom, i the relevant increment, and t the time step.

$$[K][u] = [F] \tag{1}$$

$$u^N_{(i+1)} = u^N_{(i)} + \Delta t_{i+1} \dot{u}^N_{(i+\frac{1}{2})} \tag{2}$$

In both cases, the displacement vector or matrix, u is clearly independent. Melenk introduced the concept of enriching the vector, u through the partition of unity [7], modifying the element that the crack occupies by introducing enrichment functions to estimate a solution to where the crack will propagate. In 1999, Ted Belytschko expanded upon this principle to accommodate the development of discontinuities within the finite element mesh [8].

Proper description of discontinuities is difficult and is generally defined as either a strong or weak discontinuity in the FE mesh [9]. Strong discontinuities tend to arise when there are discontinuities in the solution variables due to large displacement jumps, such as cracks and holes, whereas weak discontinuities occur due to discontinuities in the derivatives of the solution variables, resulting in strain differences, often caused by variation in material properties.

Enriched nodes are generally defined by the user with some degree of knowledge about the approximate location that a crack will develop, but the nucleation point does not have to be explicitly defined. Pre-defining the enriched crack “zone” is necessary to reduce computational time and resources.

As previously discussed, the fundamental principle behind the XFEM method is the enrichment of the displacement vector alone. Currently, Abaqus only provides capability to conduct XFEM analysis in an implicit environment. Whereas explicit solvers primarily converge on a solution which aims to solve for the acceleration of nodes and thus calculate the displacement vector from a given time-step (referring to Eq. 2), the convergence of an implicit solver is not time dependent and therefore is unconditionally stable. As seen in Eq. 3, the XFEM approach is not time-dependant, and therefore cannot be used in explicit analyses. Unfortunately, this means that for more complex structural issues with large geometries, simulations can be very inefficient due to the generation of the stiffness matrix. It should also be noted, therefore, that within the XFEM approach for modelling crack growth, it is implied that it is a “static” crack growth and therefore time-independent, making it ideal to simulate slow crack progression in low-cycle fatigue, independent of simulating an actual cyclic load.

Preliminary numerical modelling

Due to the limited background research on combining the XFEM approach with other FEM techniques on a large structural example, the first stage of validating the numerical approach is to measure the response of the numerical model of a beam section under simplified static loading conditions via a traditional FEM approach and compare the response to strain gauge data previously acquired from experimental studies (Fig. 2). The static response is compared to the pre-damage strain results (roughly <10,000 load cycles), acquired from strain gauges – SGN – mounted on the crossbeam (Fig. 3).

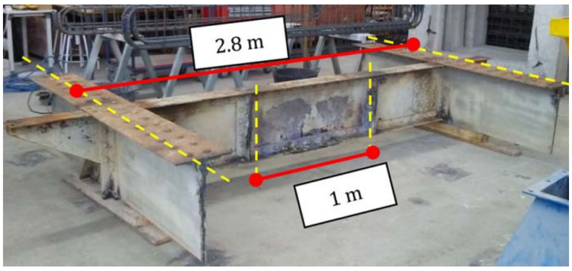

Fig. 2. Original bridge geometry of Ponte del Quisi crossbeam.

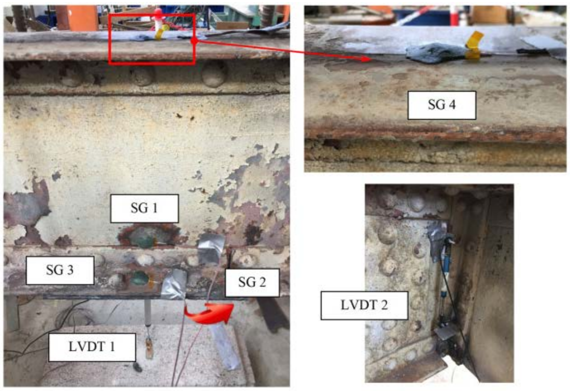

Fig. 3. Crossbeam strain gauge locations.

The geometry of the crossbeam is replicated in Solidworks/AutoCAD and exported to Abaqus. Symmetry is exploited to improve the efficiency of the simulation. The pre-process geometry, loading, and strain gauge locations are shown in Fig. 4.

The material and interaction properties are evaluated by comparing the strain results, and in addition to this, a mesh sensitivity study is carried out to ensure efficiency of the numerical model.

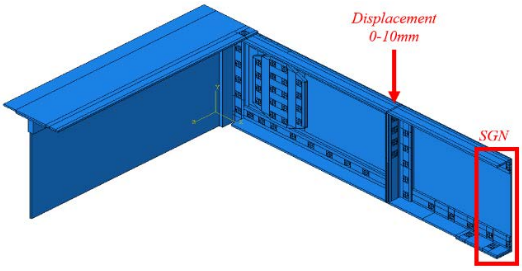

Fig. 4. Pre-process geometry of Quisi bridge.

As the model consists of many independent parts, contact interaction must be modelled to ensure realistic behaviour is captured during analysis. The coefficient of friction, v, plays a key role in the interaction between parts. It is simply defined as the relationship between the normal and reaction forces when an object moves along a surface The friction coefficient varies dramatically for given loading criteria. Due to the difficulty in determining clamping force, the normal force, R, cannot be directly determined, and therefore neither can the frictional force, F. In addition to this, the effect of material degradation on both the friction coefficient and chemical cohesiveness is difficult to determine without extensive testing. Due to the unknown characteristic of the friction of the structural steel, a range of friction coefficients from 0.14–0.74 [10], were considered for steel-on-steel friction behaviour, representing a variety of conditions from dry and clean to heavily corroded. A value for v of 0.00 was also considered to act as a control and observe whether the effect of the friction coefficient is significant.

The loading conditions are simulated by applying a simple step displacement at the point where loading from railway traffic is expected to occur via a railway track; based on the loading criteria defined in the experimental study.

RESULTS

Preliminary strain results
The strain response for a range of friction coefficients at an element size of 5mm is presented in Fig. 5.

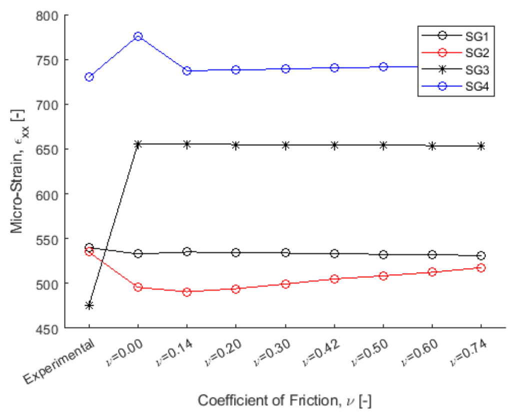

Fig. 5. Strain results using an element size of 5.

Mesh sensitivity study
Due to the size and implementation of interaction criteria, it was necessary to maximise the size of meshed elements to reduce computational time – for example, simulation run time for an approximate global element size of 5mm is roughly one hour – while maintaining accuracy of numerical results. For this purpose, a sensitivity study for elements of the following approximate global sizes was carried out (Table 1) and compared with the experimental data. Figure 6 shows the comparison between computational time required, and the percentage deviation for each strain gauge for different element sizes, using a value of v of 0.74.

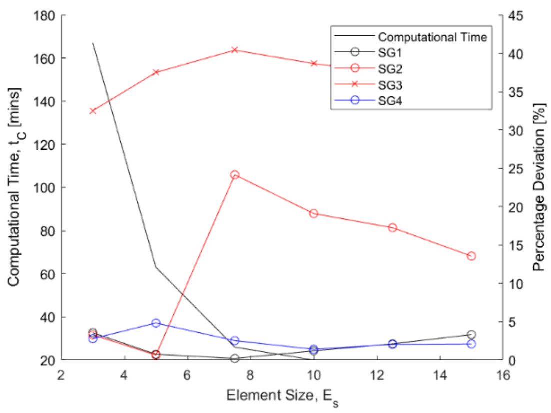

Fig. 6. Mesh sensitivity study results.

DISCUSSION

This paper presents the initial numerical work carried out investigating the response of the crossbeam, including the evaluation of the mesh. The initial results are encouraging, and using the proposed interaction and material criteria yield results within 5% deviation for all element sizes for SG1 and SG4. At a more refined mesh, the accuracy of SG2 is also within satisfactory levels of accuracy. The strain results tend to be most accurate for a higher friction coefficient, which is likely caused by high levels of steel corrosion.

The results for SG3, however, deviate significantly from the experimental results no matter the context. On the original crossbeam, SG3 is mounted on a lower plate where fatigue is seen to occur in previous experimental studies. The reduced clamping, potentially from plastic deformation in the rivet, means that in a practical scenario, the plates in the crossbeam are likely to undergo a small amount of slip, reducing the actual strain. As it is around these rivets where the maximum tensile stress and fatigue onset occurs, these potential causes will require further in-depth investigation.

A major factor to consider is the computational time required to run the simulations. A mesh sensitivity study has already been carried out, noting the computational time required, and from Fig. 5, it is possible to infer an inverse exponential relationship between the element size and computational effort. Looking ahead, the XFEM process typically requires a highly refined mesh to perform accurate analysis; if a coarse mesh can be used to accurately simulate the static response of the beam, it is proposed to use a simplified global model with a refined mesh where fatigue is expected.

Conflicts of Interest
The authors declare no conflict of interest.

Strain gauge	Experimental	E_s					
		15	12.5	10	7.5	5	3
SG1	540.00	528.57	533.49	541.13	541.13	535.90	520.77
SG2	535.00	462.45	442.65	432.76	432.76	538.47	517.34
SG3	475.00	640.97	652.51	658.61	666.94	653.12	629.47
SG4	730.00	745.33	744.96	740.29	748.51	765.25	750.40

Table 1. Mesh sensitivity results.

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