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Full paper

Robustness of Ageing Steel Bridges

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Abstract

Bridges play a fundamental role in global transportation networks, serving as cost-effective solutions for connecting two points separated by rivers, valleys, or cliffs. Among the various bridge types, steel truss bridges were commonly used in the early 1900s. This type of bridge was a preferred choice due to its ability to cover long spans with a lightweight structure and its rapid construction process. However, increasing commercial activity, climate change, and natural material deterioration have significantly impacted these bridges over the past decades. As a result, steel truss bridges, now up to 100 years old, are subjected to higher loads, extreme climate events, and deterioration processes such as corrosion and fatigue, making them an ageing infrastructure facing modern challenges. Consequently, steel truss bridges stand out as vulnerable elements within transportation networks. Replacement or retrofitting is often not affordable, necessitating the proposal of alternative solutions to address these issues. This study aimed to understand the structural response of steel truss bridges under unexpected events, such as overloads or member loss, and how these failure scenarios are managed by activating alternative load paths (ALPs). Additionally, a monitoring strategy was proposed to track variations in the bridge's structural behaviour and prevent damage propagation. The analysis was conducted through an experimental campaign on a scaled version of a real bridge. Multiple damage scenarios were evaluated to understand ALP activation and the progressive collapse potential.

Keywords

Steel Truss Bridges, Robustness, ALP’s, Progressive Collapse

1 Introduction

Bridges constitute essential components of global transport and communication networks, linking cities, regions, and countries by enabling the flow of goods, materials, and people. Their strategic significance designates them as critical points within interconnected systems, where any form of damage or failure can lead to substantial economic impacts and potentially significant loss of life [1], [2]. Furthermore, a large portion of these structures is ageing, having been exposed over time to the demands of evolving transport systems and various incidents caused by both human activities and natural events. These factors have accelerated their degradation, reducing structural capacity and heightening susceptibility to failure [3], [4]. Events such as those in Genoa and Minnesota have illustrated that the initial signs of vulnerability in bridges often appear as localised failures. Such occurrences have heightened awareness among policymakers and researchers of the need to enhance understanding for the identification and characterisation of these failures [5], [6], [7], as well as to investigate their potential development into widespread structural collapse, referred to as "progressive collapse" [8], [9].

Steel truss bridges, used from the mid-nineteenth to the twentieth century, are characterized for their long-span capability, lightweight and rapid construction. This paper explores one such bridge, focusing on localised damage detection through a monitoring approach, combining data recording with structural analysis. The aim is to understand how stability is preserved in the presence of damage through force redistribution and the activation of Alternative Load Paths (ALP).

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2 Methodology

2.1 The Bridge

The bridge under study is a historic railway structure spanning a deep ravine. Designed and constructed in the early twentieth century, the bridge was inaugurated in 1915 and, until its closure in 2023, had supported railway traffic for over a century. Supported by two masonry abutments (Fig. 1-d) and five metallic piers (Fig. 1-a), the bridge extends over a length of 168 metres and is composed of six Pratt-type metallic truss spans (Fig. 1-c), featuring two distinct configurations: four simply supported spans measuring 21 metres in length and 2.30 metres in height, and two continuous spans measuring 42 metres in length and 4 metres in height (Fig. 1-b) [10]. The bridge essentially comprises built-up sections with varying cross-sections and riveted connections. The simply supported and continuous spans consist of two Pratt truss girders interconnected by horizontal and vertical bracing systems, along with a load-transfer system that conveys railway loads to the structure. The trusses comprise verticals, diagonals, and chords; the bracing systems comprise diagonals and transversal beams; and the load-transfer system consists of stringers and transversal beams. For this study, attention was focused on one of the simply supported spans of the bridge.

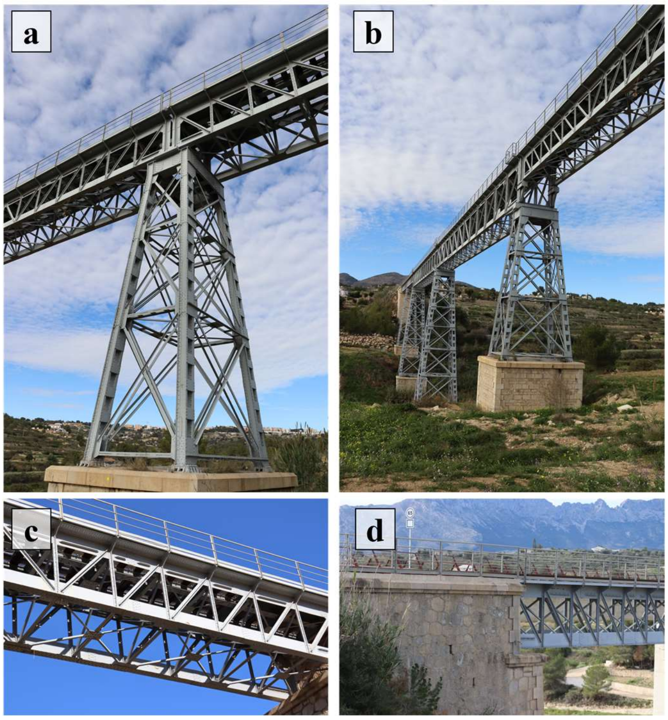

Figure 1 General View of bridge. a) bridge pier. b) entire view of the bridge. c) isostatic span. d) masonry abutments.

2.2 Experimental campaign

To analyse the bridge's response to localised failures, a scaled model was constructed to replicate the original structural behaviour accurately. Similitude theory and scale and size effects were considered to determine the scale factor and thus, the model's dimensions in order to choose standard commercial profiles to match the defined criteria.

The model consists of two 6-metre-long Pratt truss girders. Angle sections were used for the diagonals, verticals, and bracing members, while IPE profiles were used for stringers, chords, and upper transverse beams. For boundary conditions, the supports were designed to allow rotations at the ends of the bridge, allowing longitudinal movement at one of its ends. The loading system was thought with two objectives: to replicate realistic railway loading and to stimulate structural responses.

The experimental campaign was conducted at the Institute of Concrete Science and Technology (ICITECH) facilities at the Universitat Politècnica de València. The test setup was assembled by placing the scale model and supports on the reaction floor and then positioning the hydraulic jack to ensure alignment with the bridge's centre. With the bridge and hydraulic jack in position, the load application system was installed, consisting of steel profiles required to distribute the load across various points of the structure.

9 damage scenarios were tested to simulate sudden local failures, where the disconnection of structural elements impacted the overall behaviour of the bridge. The components to be disconnected were selected based on computational simulations, which helped to identify the most stressed under realistic, unfavourable loading conditions. The disconnection was carried out using an angle grinder, cutting the component after initial loading cycles (undamaged state), followed by reloading of the damaged structure. After each test, the removed element was repaired to recover the structure's original stiffness. The experimental programme was therefore divided into nine sub-tests, removing horizontal bracing, vertical bracing, bottom chords, and vertical and diagonal members. Damage scenarios, labels, and photos are presented in Fig. 2, with the removed elements highlighted in magenta in Fig. 3.

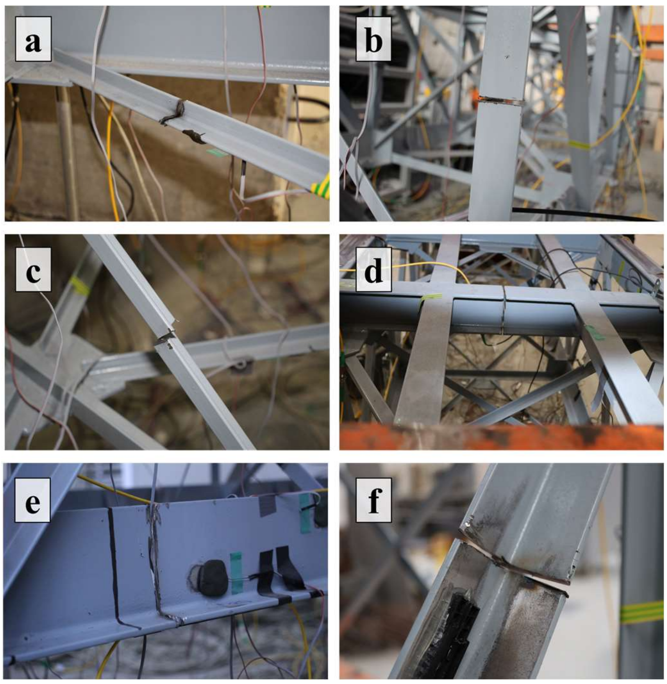

Figure 2 Damage Scenarios. a) Partial and total horizontal bracing removal (HB). b) Vertical removal (vertical). c) Partial and total vertical bracing removal. d) Partial and total transversal beam removal (TB). e) Bottom chord removal (Chord). f) Diagonal removal (Diagonal).

Displacement transducers and strain gauges were positioned along the structure with their locations carefully chosen through computational simulations, ensuring responsiveness to changes and reliable capture of response variations. Displacement transducers were placed near the lower connections of the trusses, while strain gauges were positioned in the diagonals, verticals, chords, bracing systems, and stringers. The full sensor layout is shown in Fig. 3, where arrows with blue text identify displacement transducers, arrows with black text indicate gauges on the chords, and other gauges are directly marked on the respective elements in bold text.

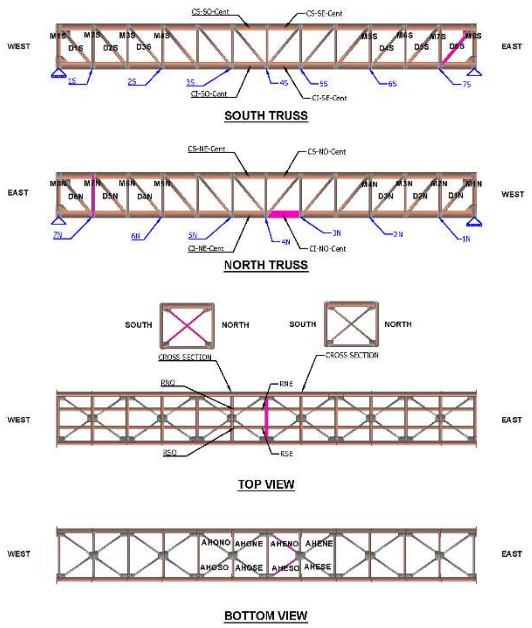

Figure 3 Monitoring and removed elements' location

3 Results

For the analysis of the results, relative differences were used as a key indicator. The relative difference quantifies the percentage change in a system variable when it is subjected to a modification. In this case, the primary variables of interest are vertical displacements and strain measurements, with the states of interest being "Undamaged" and "Damaged," where the removal of elements corresponds to the transition between these states. The relative differences are calculated as outlined in Eq. 1.

$$R_{D,x}[\%] = \frac{x_D - x_{UD}}{x_{UD}} \cdot 100 \quad (1)$$

Where RD corresponds to the relative difference of a given variable x, with x_D represents the variable's measurement in the damaged state and x_{UD} in the undamaged state. It is important to note that the value of relative differences indicates the variable's sensitivity to the damage scenario. In the case of strain gauges, this means loading processes (R_D > 0%), unloading processes (0 ≥ R_D > -100%), and/or load reversal (R_D < -100%).

3.1 Displacements

The analysis starts by examining the relative differences in vertical displacements. As shown in Fig. 3, displacements were measured at the lower nodes of the trusses, where the verticals, bottom chords, and diagonals connect. The results and relative differences are presented in Fig. 4 and Fig. 5.

From these figures, it is clear that the sensors are highly sensitive to changes in displacement. When the results are analysed by its respective damage scenario, it is observed that the loss of the bottom chord reduces the vertical stiffness of the bridge, causing displacements on both sides, with relative differences exceeding 20%. In contrast, when either the diagonal or vertical is lost, the undamaged side experiences minimal changes in displacement, with some even decreasing, while the damaged side shows increasing relative differences, particularly near the damage site. This pattern suggests torsional effects due to the imbalance caused by the loss of the bottom chord.

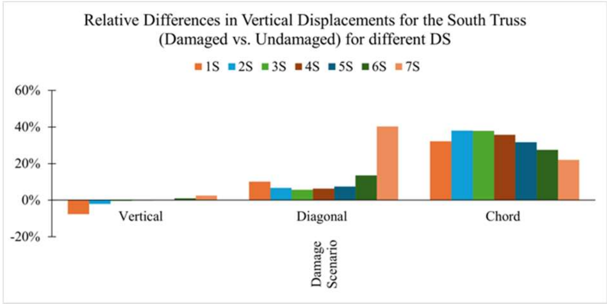

Figure 4 Relative Differences in Vertical Displacements for the South Truss (Damaged vs. Undamaged) for different DS

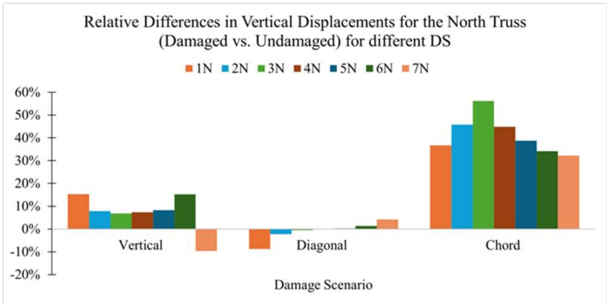

Figure 5 Relative Differences in Vertical Displacements for the North Truss (Damaged vs. Undamaged) for different DS

3.2 Strains in the bracing system

The response of the central bottom bracing system was examined for the damage scenarios involving the removal of the vertical bracing, diagonal, and bottom chord. The results, presented as relative differences, are shown in Fig. 6 and Fig. 7.

As indicated in Fig. 6, the horizontal bracing system displays significant relative differences, exceeding 100%, emphasising the critical role of these elements in load redistribution and their sensitivity to the loss of the bottom chord. When the bottom chord is removed, the bracing systems serve as a primary load redistribution path between the trusses, transferring loads by increasing their internal axial forces.

In contrast, Fig. 7 shows the relative differences for the horizontal bracing in scenarios where the vertical bracing, diagonal, or vertical element is removed. In these cases, the relative differences vary between 5% and 10%, with alternating patterns linked to the activation of axial resistance, which helps control the torsional effects caused by the failure of these elements.

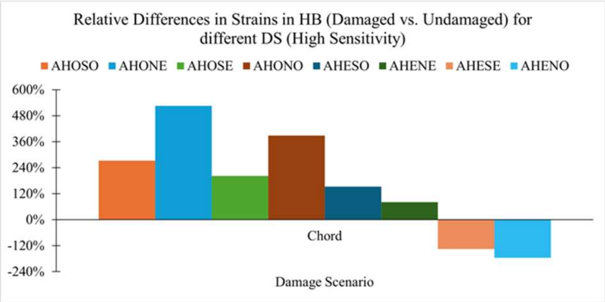

Figure 6 Relative Differences in Strains in HB (Damaged vs. Undamaged) for different DS (Moderate Sensitivity)

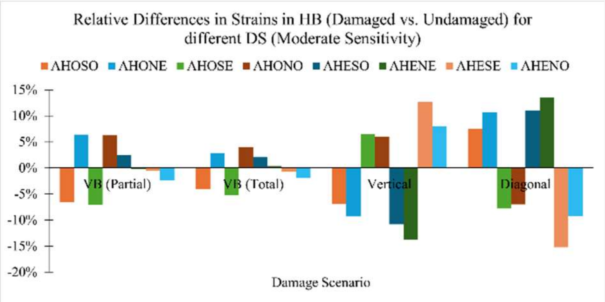

Figure 7 Relative Differences in Strains in HB (Damaged vs. Undamaged) for different DS (High Sensitivity)

3.3 Strains in central chords

The strain response in the central chords can be classified into three categories based on their sensitivity, as indicated by the magnitude of relative differences. The highest sensitivity was observed in scenarios where the bottom chord and transversal beam were removed (RD > 10 %), followed by cases where either the diagonal or the vertical was removed. In contrast, the removal of the central vertical bracing system produced minimal response. The results for the damage scenarios with the greatest sensor sensitivity are shown in Fig. 8 and Fig. 9.

It is evident that the loss of the bottom chord significantly affects strain relative differences in the adjacent chords. The damaged side shows strain reductions of up to -80 %, while the undamaged side experiences relative differences exceeding 80 %. This suggests a load transfer between the trusses, which is reflected in the changes to the strain distribution. Removing one of the bottom chords reduces the bending resistance, forcing the structure to re-establish equilibrium by redistributing forces in the remaining chords.

For the removal of the central transverse beam, the upper chords show strain relative differences exceeding 10 %, a result of the bending moments transferred from the released beam to the chords.

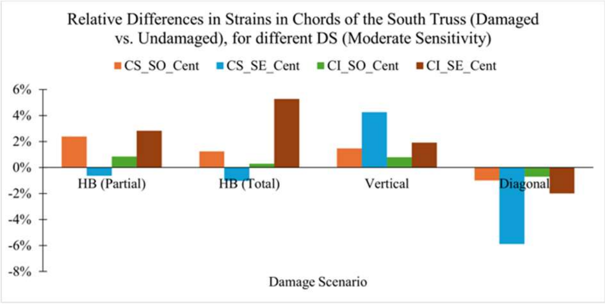

Figure 8 Relative Differences in Strains in Chords of the South Truss (Damaged vs. Undamaged) for different DS (High Sensitivity)

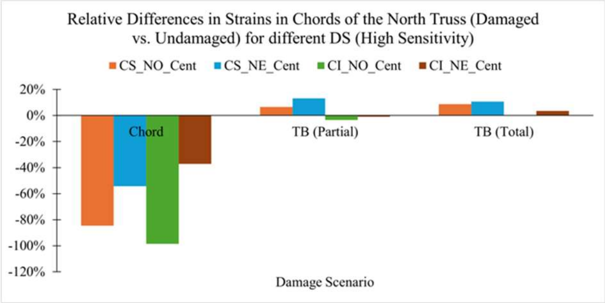

Figure 9 Relative Differences in Strains in Chords of the North Truss (Damaged vs. Undamaged) for different DS (High Sensitivity)

The relative differences in strain for the chords with moderate variability are presented in Fig. 10 and Fig. 11. While the sensitivity is below 6%, certain behavioural patterns can still be detected, linking the strain relative differences to specific types of damage. Notably, the removal of the horizontal bracing system leads to an increase in strain in the chords adjacent to the damaged area. This is due to bending demand, which was previously absorbed by the lower horizontal bracing, being redistributed to the neighbouring chords, creating a localised response to the damage.

In contrast, the damage scenarios involving the removal of the diagonal and/or vertical elements display a similar behaviour to the removal of the bottom chord. In these instances, the chords in the damaged truss show reductions in their relative differences, while the undamaged truss exhibits an increase. This suggests that the damaged truss experiences a reduction in load-carrying capacity, while the undamaged truss takes on a greater share of the applied load.

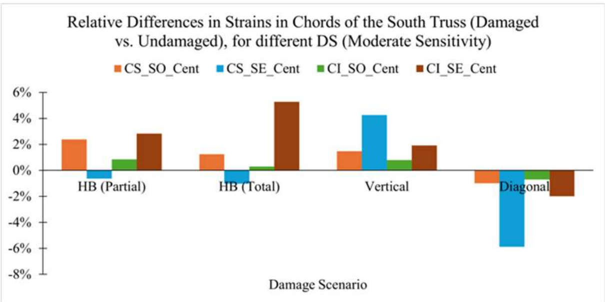

Figure 10 Relative Differences in Strains in Chords of the South Truss (Damaged vs. Undamaged), for different DS (Moderate Sensitivity)

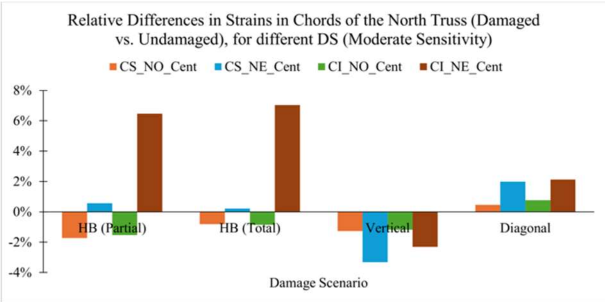

Figure 11 Relative Differences in Strains in Chords of the North Truss (Damaged vs. Undamaged), for different DS (Moderate Sensitivity)

3.4 Strains in verticals

Figures 12 and 13 show the relative differences in vertical displacement for three damage scenarios: removal of the vertical, diagonal, and bottom chord. It is evident that the loss of either the vertical or diagonal element leads to a significant localised response in the verticals adjacent to the damage. In both cases, some verticals near the damaged area display relative differences lower than -100 %, indicating the development of bending moments in the damaged truss. In a secondary proximity range, relative differences exceeding 10 % are observed, suggesting force redistribution through the nearest available path.

In the damage scenario where the bottom chord is removed, the verticals in the undamaged truss show relative differences around 20 %, while their counterparts in the damaged truss exhibit approximately -20 %. This clearly demonstrates the redistribution of load between the two trusses.

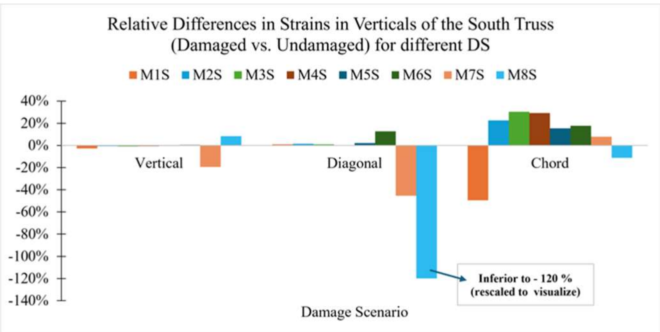

Figure 12 Relative Differences in Strains in Verticals of the South Truss (Damaged vs. Undamaged) for different DS

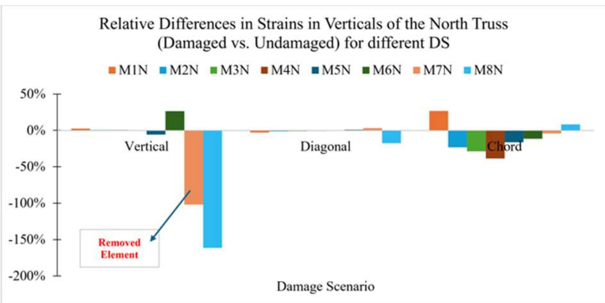

Figure 13 Relative Differences in Strains in Verticals of the North Truss (Damaged vs. Undamaged) for different DS

4 Conclusions and further work

This article presents relevant results regarding the structural response of a metal truss bridge and the influence of different damage scenarios on this response. A scaled model of a representative bridge of this typology (Pratt) was constructed, with loads applied to simulate operational conditions. The damage scenarios were recreated by cutting elements from the main structure of the truss (diagonal, vertical, and chord), the load transfer system (transverse beam), and the bracing systems. Finally, the structural response was recorded through multiple sensors, with particular attention to those exhibiting higher degrees of change between the undamaged and damaged states.

In this way, the analysis of the results obtained from the experimental campaign allowed for the identification of how the variations in the sensor measurements were related to the bridge's response, depending on the recreated damage scenario. It was shown how displacements and strains correlate with load transfer phenomena between the trusses, activation of torsional resistance, and bending mechanisms in the vicinity of the damage within the truss plane. Additionally, the analysis confirmed that, despite the presence of damage, structural stability is achieved through force redistribution and the activation of alternative load paths. As a result, the progression of damage is effectively controlled, preventing the onset of progressive collapse. Furthermore, damage scenarios involving elements from the main structure of the truss exhibited distinctive patterns in the structural response.

Finally, the need for a combined analysis integrating the response of multiple sensors is emphasised to accurately identify the type and location of damage. The work presented in this research corresponds to the initial phase of an analysis that will be developed in future studies. Patterns and relationships between the structure's response and the variations recorded by the sensors will be established to characterise how the structure modifies its behaviour by redistributing loads through alternative load paths (ALP). In this way, the mechanisms that ensure structural stability and control progressive collapse in damaged conditions will be further clarified.

5 Acknowledgments

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