ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

Check for updates

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023

Ernst & Sohn A Wiley Brand

Preventing failure propagation in steel truss bridges

Ana Sánchez-Rodríguez[1] | Santiago López[2] | Nirvan Makoond[1] | Manuel Buitrago[1] | Belén Riveiro[2] | José M. Adam[1]

Correspondence

José M. Adam
Universitat Politècnica de València
ICITECH
Camino de Vera s/n
46022, Valencia, Spain
Email: joadmar@upv.es

[1] ICITECH, Universitat Politècnica de València. Camino de Vera s/n, 46022, Valencia, Spain
[2] CINTECX, Universidade de Vigo, GeoTECH Group. As Lagoas, Marcosende, 36310, Vigo, Spain

Abstract

Metal and steel truss bridges are essential for transportation networks worldwide but are vulnerable to collapse due to deterioration and increasing traffic loads, particularly for ageing structures. Several bridge collapses, such as the Seongsu bridge (South Korea, 1994), I-35 bridge (USA, 2007), and Chauras bridge (India, 2012), have highlighted the need to develop accurate robustness assessment strategies and efficient mitigation of collapse risks. This paper summarizes results of experimental and computational studies for a steel riveted bridge with a truss-type structure. The experimental component presented involves unique tests to be performed on a 21 m full-scale bridge span subjected to the failure of different elements under laboratory conditions. The paper then presents a first approach to explore different damage and failure scenarios for steel truss bridges, which will assist in defining data collection strategies for optimised monitoring and developing data analysis methods for real-time diagnosis of ageing bridges. With this, the paper contributes to avoiding progressive collapses and presents a framework, developed as part of an ongoing project, to identify vulnerable zones for prioritising monitoring systems that anticipate failure propagation and prevent collapse. The framework is based on a systematic analysis of past bridge failures and simulations of carefully designed generic cases.

Keywords

Truss-type bridges, Structural robustness, Large-scale tests, Numerical modelling, Failure analysis

1 Introduction

Transportation networks are critical to the functioning of modern societies, and bridges are essential components of these networks. However, ageing bridges are particularly vulnerable due to their exposure to deterioration processes over time and higher loads than those considered when they were designed. Such vulnerability is evident from the increasing number of accidents related to ageing bridges, leading to significant losses for society. Progressive collapse is a phenomenon that can cause such accidents, as localised failures can propagate through the structural system and trigger catastrophic collapse. This type of collapse due to a localised structural failure has resulted in a significant number of deaths, injuries, and economic losses. Historical and recent examples include bridges over the Birz river (Switzerland, 1891), the Quebec bridge (Canada, 1907), the I-35 bridge (USA, 2007), or the Chauras bridge (India, 2012) [1–4]. Studies carried out in the United States in an eleven-year period (1989-2000) have shown that the dominant types of failed bridges are steel beam/girder and steel truss bridges, accounting for more than 50% of the collected bridge failures in the US [5]. These findings highlight the significant occurrence and susceptibility of steel truss bridges, which serves as motivation for investigating methods to prevent their progressive collapse.

Common causes of collapse in steel bridges include natural disasters, overloads, and design deficiencies. Local failures may occur due to stress concentrations, weathering, and water penetration, leading to a chain reaction that results in the progressive collapse of the entire structure. Preventing and identifying local failures or damages in vulnerable bridges is crucial and involves developing adequate inspection, analysis, maintenance, and monitoring strategies. Local failures can occur due to multiple reasons or sudden damage and produce significant structural changes in areas other than where the damage occurs, which can be identified through monitoring.

Structural health monitoring (SHM) strategies have been developed to identify potential failures in ageing bridges and to optimize maintenance activities. However, most monitoring solutions available today require large expensive sensor systems and significant computational re-

https://doi.org/10.1002/cepa.2377

sources, making their application on a large-scale challenging. This paper is framed within the *Pont3* project (www.pont3.es), a coordinated research initiative funded by the Ministry of Science and Innovation of Spain and the European Regional Development Fund under Grant Agreement PID2021-124236OB. This project addresses the presented issue by developing a novel, holistic, and cost-effective approach to anticipate the failure propagation of ageing bridges and avoid catastrophic collapses. This approach will involve identifying and prioritising local failures or damages that can cause cascading effects, and developing cost-effective monitoring configurations to detect them. The monitoring system will use ultra-efficient data analysis procedures to update specifically designed risk indicators in real-time for supporting decision-making processes. The primary scientific and technical contribution of *Pont3* lies in the advancement of monitoring strategies and methods, facilitating the large-scale application of bridge monitoring solutions to enhance the safety and resilience of bridges.

This paper introduces basic concepts important for the development of such a project. In addition, it also presents a first approach to study different damage and failure scenarios for steel truss bridges. This will help in the definition of data collection strategies for optimised monitoring, as well as in the development of data analysis methods for real-time diagnosis of aging bridges. With this, the paper can contribute to avoiding progressive collapses. The paper will focus on one of the most common types of ageing bridges, steel truss bridges. The structure of this document starts with the summary of related previous work, directly affecting the execution of this paper (Section 2). Then, an introduction to general concepts is done, including truss bridge typologies and damage and failure definitions (Section 3). Section 4 presents a first attempt for the definition of different damage and failure scenarios, classified into different categories. Later, Section 5 introduces the case studies in use to define the vulnerable zones of steel truss bridges, and finally Section 6 summarises the conclusions of this paper.

2 Previous work

This section provides a comprehensive summary of previous studies conducted by the research team on the topic. It offers an overview of key findings and insights gained from earlier work.

Bertolesi et al. (2021) presented a work performing a fatigue assessment of a steel riveted railway bridge [6]. The study focused on investigating the fatigue behaviour of two steel truss bridges that are part of the Spanish national railway network. The research involved an experimental investigation, which included fatigue testing of a full-scale bridge span (Figure 1) and an upper cross beam. Focusing this summary on the first one, a cyclic load ranging from 50 to 1300 kN was applied (0.2 Hz). The fatigue test comprised 45,000 load cycles, equivalent to an additional 27 years of operational service of the bridge.

The testing utilized Linear Variable Displacement Transducers (LVDTs) and Strain Gauge (SG) sensors to capture possible nucleation and propagation of fatigue cracks within the bridge structure. The results of this fatigue test were used to calibrate an elastic numerical model of the entire structure, which was then utilized to estimate the remaining fatigue life of one of the bridges. Additionally, an analytical evaluation was conducted to determine the bridges' remaining fatigue life, taking into account rolling loads. Considering an appropriate behaviour under fatigue loading up to a damage level of 7.2%, as well as future traffic volume and characteristics and the S–N curves methodology, the authors estimated that the structure could endure approximately 320,000 additional cycles.

The study identified the cross beams as the most vulnerable elements of the bridges, and fatigue failures were expected to arise in the next decade due to normal stresses. Overall, the research represents an important step towards understanding the fatigue responses of ageing riveted steel bridges, utilizing a unique double experimental investigation encompassing comprehensive laboratory tests and numerical modelling techniques.

Then, Buitrago et al. (2021) published an article studying the robustness of the same two bridges [7]. The study conducted experiments on the robustness of riveted steel bridges based on truss-type structures, and aimed to provide practical recommendations for detecting local failures before they cause progressive structural collapse. The study used a 21 m full-scale bridge span (Figure 1) tested under laboratory conditions with an extensive monitoring system, as well as a linear-static finite-element analysis to examine other possible causes not included in the experiment. The results showed the structural redundancy of truss structures based on the joints' resistance to bending moments and provided recommendations for identifying early failures and avoiding progressive collapse. The study also found that the structure had the ability to adapt to the total failure of key elements, such as diagonals, thanks to the effective activation of alternative load paths (ALPs), changing its behaviour from that of a Pratt truss to Vierendeel or single-beam behaviour. The study provided practical recommendations for structural health monitoring, recommending different control parameters as well as types and locations of sensors for both basic and extensive monitoring systems. These recommendations were used to design monitoring systems for three real bridges which are still providing real-time information on structural health at present. One of these bridges was equipped with an ambitious monitoring system consisting of more than 400 sensors.

The present article continues the work previously developed and serves as a basis for the *Pont3* project. The idea is to define failure scenarios and analyse the case studies considering both threat dependent and threat independent failure scenarios by leveraging the knowledge acquired from the preceding research outlined herein.

Figure 1. Laboratory testing of a full-scale 21-metre bridge span

3 General concepts

3.1 Typologies of truss bridges

Truss bridges stand as impressive examples of structural engineering, showcasing the interconnectedness of slender elements working harmoniously under axial loads. The design philosophy behind these structures revolves around optimizing load distribution. Truss bridges can be classified based on their primary structural behaviour into three general categories: truss beams, truss arches, and truss cantilevers. Each of these categories has distinct subcategories or types. Many structures consist of a combination of these types and give rise to hybrid solutions. In this section, the classification of truss bridges is discussed.

A. Truss beams

According to the overall primary structural system, they can be classified as:

i. Simply supported truss

Usual configurations may be of constant or variable depth. When the shape of the top chord is parabolic, this type of truss is often named *bow-string truss*.

ii. Continuous truss

They often have a variable truss depth to optimise the structural performance. Note that they can be through bridges or upper-deck bridges.

iii. Gerber type truss (see C.i.).

B. Truss arches

i. Fixed supports

This is a rare category: although fixed supports were used in cantilever construction, the fixity was usually released after the arch was closed.

ii. Hinged supports

Most truss arch bridges have hinged supports. The arch may be of constant depth or variable depth. Note that different positions of the deck are possible.

iii. Bowstring arch

Composed of an upper arch (often parabolic), and a deck in tension with vertical (usually rigid) suspensions. The overall scheme is the same as that of a simply supported beam; no thrust is introduced in the abutments. Light bracing members to improve the performance against non-symmetric loads can be present. This kind of structure is sometimes difficult to categorise as arches or beams of variable depth; they often have a hybrid behaviour.

C. Cantilever trusses

i. Gerber truss

They have a simple supported span resting on two cantilevering parts to achieve an overall statically determinate scheme. This configuration is, in many cases, transformed to a continuous one after finishing the construction by adding additional members to block the support of the simple span.

ii. Cantilever truss with a simply supported central span

It has several similarities with the Gerber-type scheme. In this case, the cantilevering part is fixed to the foundation.

iii. Cantilever truss without a simply supported central span

This is an unusual type of bridge. It can be arguably classified as a three-hinged arch.

According to the arrangement of truss members, a widespread alternative classification originated from the different patents that were used in the 19th century. Nowadays, the most usual types are as follows (note that there are many other non-listed less-common arrangements):

- Howe truss: diagonal members are in compression under self-weight. This is a less common arrangement in steel bridges (compression is generally avoided in design).
- Pratt truss: diagonal members are in traction under self-weight.
- Warren truss: alternating compression-traction diagonal members.
- Lattice truss (town truss): dense diagonal net in both directions.
- Vierendeel truss: they lack diagonal members. Joints are designed to resist local bending moments.

3.2 Damage and failure

Performing a correct risk assessment requires the identification of all hazards that can cause undesirable events (initial damages or failures) during the life cycle of a structure, in this case a bridge. There are several standardised definitions referring to "hazard", as shown in Table 1. In *Pont3*, the definition proposed by ISO 2394:2015 (General principles on reliability for structures) [8] is being followed. The mentioned standard defines also different categories of hazard that should be considered when analysing a structure. According to ISO 2394:2015, three different categories may be identified1: i) natural or general human activities; ii) human-made actions (vandalism and malicious attacks); and iii) errors and negligence.

The subsequent natural step should be to define 'damage' and 'failure', which are the consequences generated by a hazard in a structure like a truss bridge. The project DURATINET [9], funded by the European Union, presented a classification of damage causes and processes. This was supported also by a more recent study, the COST Action TU1406, called "Quality specifications for roadway bridges, standardization at a European level" [10]. In this Action, the authors studied the different categorization of damages depending on the type of structure and also analysed the relation of these damages with observations, damage indicators, performance indicators and key performance indicators, according to their nomenclature. As a conclusion, it can be said that the "damage causes" proposed by these works are actually hazards (and categories of hazard), as defined by ISO 2394:2015 [8].

The COST Action TU1406 also provides a definition of damage as a "process that has a detrimental effect on a bridge, and that may act singly or in combination to generate safety and serviceability problems" [10]. In the context of bridges, damage may be caused by factors such as excessive loads, corrosion, or natural disasters. On the other hand, the ISO 13824:2020 standard defines failure as a "state which does not meet the required performance objectives due to structural damage and/or loss of function" [11]. Considering this definition, it seems obvious to relate failure with damage and clearly differentiate both terms. This definition distinguishes between failure and damage, with damage being a necessary but not sufficient condition for failure. In other words, damage to a structure does not necessarily mean that the structure has failed, but a structure that has failed must have experienced some form of damage. By considering this, it is possible to identify the underlying causes of damage and take steps to prevent or reduce the likelihood of failure. This can help to ensure the safety and reliability of the structure over its entire life cycle.

Hazards can cause specific constituents (elements) of a structural system to reach a particular damage state or to fail. It is important to distinguish between the failure itself and the failure mode.

Table ***2*** shows standardised definitions for these two concepts, which should be taken into consideration when working in this project.

In this paper as well as in the *Pont3* project, the aim is to identify plausible initial constituent damage states or failures that have a high probability of resulting in high-consequence system failure states (see Figure 2). It is important to understand the different possible failure modes and their effects to be able to achieve this. However, the starting point for studying possible propagation mechanisms should be defining constituent damage states or initial constituent failures. Having said that, a preliminary list of relevant failure modes for steel elements that should be considered when defining the initial constituent damage states or failures of interest can be obtained by examining the Ultimate Limit State (ULS) verifications that need to be performed according to Eurocode 3 [12]. Some of these are listed subsequently. In the next section (Section 4), initial scenarios are proposed based on the information provided here.

- Resistance of cross-sections to axial tension
- Resistance of cross-sections to axial compression
- Resistance of cross-sections to bending moments
- Resistance of cross-sections to shear
- Resistance of cross-sections to torsion
- Resistance of cross-sections to local transverse forces
- Resistance to flexural buckling (with and without axial forces)
- Resistance to torsional buckling
- Resistance to lateral-torsional buckling

Table 1 Standardized definitions of hazard

Reference	Definition
ISO Guide 73:2009	Source of potential harm[2]
ISO 13824:2020	Potential source of undesirable consequences.
IEC 31010:2019	Potential source of danger, harm, or other undesirable outcomes [3,4,5]
ISO 2394:2015	Unusual and severe threat, e.g. a possible abnormal action or environmental influence, insufficient strength or stiffness, or excessive detrimental deviation from intended dimensions.
fib Model Code 2010:2013	An occurrence which has the potential to cause deterioration, damage, harm or loss.
EN 1990:2002	For the purpose of EN 1990 to EN 1999, an unusual and severe event, e.g. an abnormal action or environmental influence, insufficient strength or resistance, or excessive deviation from intended dimensions.

Table 2 Standardized definitions of failure and failure mode

Reference	Definition

---

[1] In some situations, it is possible for one hazard to be followed by another, resulting in much more serious consequences to a structural system. [8]

[2] Hazard can be a risk source. [8]

[3] The term hazard in IEC 31010:2019 is referred to as threat. [17]

[4] A threat is a negative situation in which loss is likely and over which one has relatively little control. [17]

[5] A threat to one party may pose an opportunity to another. [17]

Failure ISO 13824:2020 (Bases for design of structures — General principles on risk assessment of systems involving structures)	State which does not meet required performance objectives due to structural damage and/or loss of function. Note: Failure includes insufficient load-bearing capacity or inadequate serviceability of a structure or structural member, or rupture or excessive deformation of the ground in which the strengths of soil or rock are significant in providing resistance.
Failure mode EN 13306:2010 (Maintenance. Maintenance terminology)	Manner in which the inability of an item to perform a required function occurs.* ** *Note: The use of the term "fault mode" is deprecated. **Note: A failure mode may be defined by the function lost or the state transition that occurred.

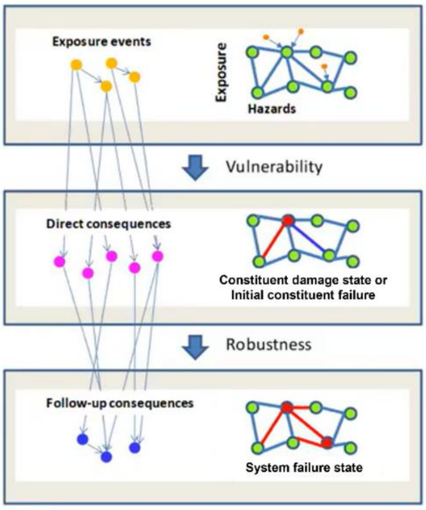


Figure 2 Schematic illustration of vulnerability and robustness (adapted from [13])

4 Initial scenarios

Considering the concepts introduced in Section 2, the following situations that can lead to initial constituent failure have been identified as being particularly relevant for steel truss bridges:

- High compressive stress along the top chord
- High compressive stress along the bottom chord
- High compressive stress on diagonal members
- High tensile stress along diagonal members
- High compressive stress on vertical members
- High forces at specific joints
- High bending/shear in floor beams
- Corrosion
- Repetitive or cyclic loads
- Geometric imperfections on elements in compression

In addition, it is important to identify the most vulnerable zones of the truss bridge, since those are likely to be the first to suffer from failure. The COST Action TU1406 defines vulnerable zones as "the segments and or elements of a bridge structure in which damages have the largest impact on safety and serviceability. One vulnerable zone may be related to several failure modes" [10]. Adapting this definition to what was defined in Section 3.2, the vulnerable zones of a bridge will depend on the loading conditions of the bridge (i.e., considering traffic loads, wind, etc.).

Based on all the information presented, the following types of initial constituent damage states and failures have been defined. It is important to highlight that the focus is on the state of the constituent rather than on the hazard or damage process leading to that state.

Types of initial constituent damage states or failures to study

A. Complete rupture of bar elements

This failure is characterised by the complete separation of a bar element into at least two parts [14]. In this state, it can be considered that the entire bar element no longer contributes as part of the structural system to resist actions imposed on it.

There are many situations which can cause such failures. For instance, if the imposed actions exceed the capacity of structural elements as defined by several of the ULS verifications included in EC3. It could be relevant to study the propagation potential of such ruptures in transverse beams that support the deck, in elements of the upper or lower chord, and in any other bars of the steel truss. Some relevant simultaneous component failures may also have to be considered.

B. Partial loss of cross-section of beams or bar elements at point location

This state can be considered as equivalent to a partial testing (perpendicular) cut through the cross-section of a beam or bar element at a local point along its length. A specific percentage of cross-sectional area loss can be set to ensure the damage state is well-defined. Such a state can arise due to localised pitting corrosion. It can also represent an intermediate stage of a fatigue crack (prior to total rupture) [15], attending to the ISO 10721-1:1997 definition of fatigue (*damage by gradual crack propagation in a structural part, caused by repeated stress fluctuations*) [16].

The same elements described as being relevant for studying type A constituent failures (transverse beams, any bars of the steel truss) are also relevant for the type B constituent damage state.

C. Uniform loss of cross-section of beam or bar elements

The ISO 8044:1999 defines corrosion as a *physicochemical interaction*[6] *between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part* [15]. Following this definition, state "C" refers to a generalised and distributed loss of the cross-sectional area of a beam or bar element and can occur due to corrosion. Once again, a specific percentage of cross-

---

[6] This interaction is often of an electrochemical nature.

sectional area loss can be set to ensure the damage state is well-defined.

The same elements described as being relevant for studying type A constituent failures (transverse beams, any bars of the steel truss) are also relevant for the type C constituent damage state.

D. Joint/connection failure

There can be many different types of connections between different bars in a steel truss bridge and it could be relevant to study the propagation potential of several of them.

This failure is characterised by the total or partial loss of connection between two elements, thus preventing them from working together at all or at least in a proper way. Several of the hazards mentioned in Section 3.2 can lead to such failures.

E. Differential settlement of support

This state is characterised by an asymmetrical settlement of one (or more) supports of the steel truss. This can impose abnormal stresses for which truss elements were not designed for.

Different plausible configurations of supports can be selected to define relevant scenarios to be studied for any case. This should also include the magnitude of displacements that can occur at each support location.

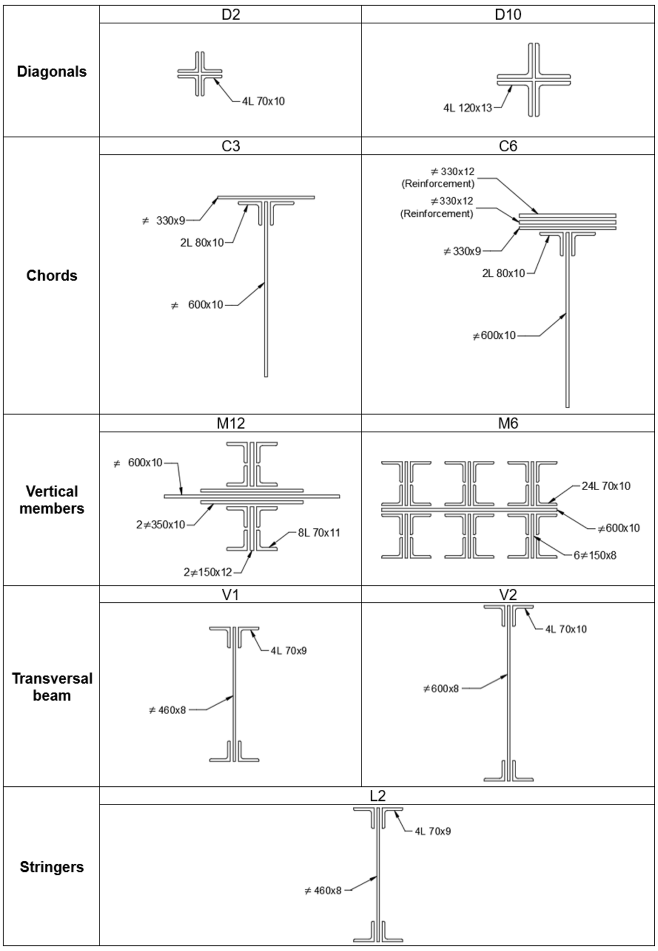
5 Case study

To develop and test the methodology for identifying vulnerable zones and define damage and failure scenarios, a Pratt truss bridge was chosen as a case study. Specifically, the Quisi bridge placed in Valencia (Spain) was selected (Figure 3). The main reasons for this selection are that Pratt-type bridges are the most common truss bridges in Spain, and because this bridge is being currently monitored in real time by some authors with more than 250 sensors. It is approximately 170 m long and composed by 6 spans, whose lengths vary from 21 to 42 m, resting on two lateral abutments and five steel truss columns of different heights. The two central spans form a continuous hyperstatic beam, while the others were constructed as isostatic elements [6].

Figure 3. Real case study. Quisi bridge (Valencia, Spain). General view

The truss of the Quisi bridge is intricately designed with a combination of different profiles for each type of element. Each of these types is carefully configured with specific profiles to meet the required load-bearing characteristics. For instance, diagonals may have various profiles with slight variations in measurements but maintaining the same shape to optimize their structural performance. Similarly, other elements such as struts feature distinct profiles tailored to their specific roles within the truss system. The utilization of different profiles enhances the truss's overall strength, stability, and load-carrying capacity, allowing it to efficiently distribute forces and stresses throughout the bridge structure. **Error! Not a valid bookmark self-reference.** presents a selection of the most relevant profiles employed in the construction of the Quisi bridge's truss. These profiles exhibit variations in dimensions, such as cross-sectional dimensions, lengths, and geometries, depending on the specific element type and its location within the truss assembly.

Table 3. Structural details of some critical elements



To create models of the Quisi bridge, the software SAP2000 was chosen. This software is commonly used in the field of civil engineering for structural analysis and design. For the purpose of this article, only the hyperstatic spans were analysed, so that the stiffness of the structure is considered. The 3D model of the bridge was developed taking into account the geometry and material properties of the different structural members (Figure 4).

Using this model, a series of analyses were conducted to identify the most vulnerable zones of the bridge (Figure

5). Specifically, the stresses and strains experienced by the different members of the truss were analysed under various loading conditions, considering only traffic loads and the own weight of the bridge.

Having identified these vulnerable zones, this information will be used to develop initial damage and failure scenarios. For example, the effects of the failure of a gusset plate could be simulated, or the failure of a diagonal member in the centre of the span. In a later step, these scenarios will be analysed to develop specific monitoring strategies to detect the damage states before they lead to the progressive collapse of the bridge.

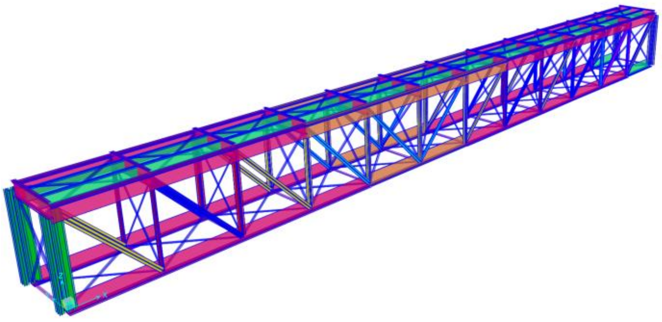


Figure 4. 3D model of a 21 m span of Quisi bridge. Analyses conducted with both hyperstatic spans of the bridge to consider the stiffness of the structure

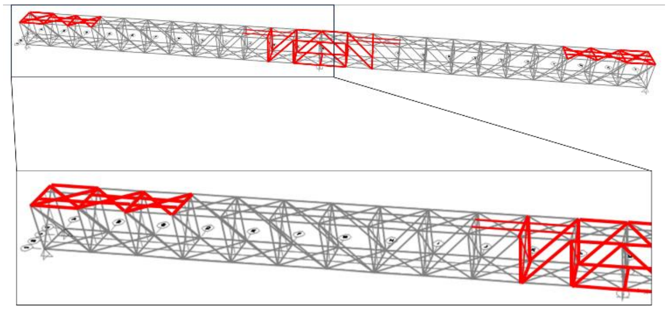


Figure 5. Most tensioned elements in the model. Load combination: traffic load (train) and dead load

6 Conclusion

Truss bridges are one of the most common types of bridges used in modern infrastructure. Damage and failure in these structures can result from various hazards, including natural disasters, human-made actions, and errors or negligence. To ensure the safety and reliability of a truss bridge throughout its entire life cycle, it is necessary to identify the underlying causes of damage and take steps to prevent or reduce the likelihood of failure.

This article helps to identify plausible initial constituent damage states or failures that have a high probability of resulting in high-consequence system failure states. This is achieved by understanding the different possible failure modes and their effects on the structure.

Overall, the analysis of the Quisi bridge using SAP2000 and the subsequent identification of vulnerable zones highlight the importance of understanding the vulnerabilities of aging steel truss bridges. By identifying these vulnerabilities and developing appropriate monitoring and maintenance strategies, it is possible to prevent future collapses and ensure the safety of infrastructure.

References

[1] M.V. Biezma, F. Schanack, Collapse of Steel Bridges, Journal of Performance of Constructed Facilities. 21 (2007) pp. 398–405. https://doi.org/10.1061/(ASCE)0887-3828(2007)21:5(398).

[2] H.S. Birajdar, P.R. Maiti, P.K. Singh, Failure of Chauras bridge, Engineering Failure Analysis. 45 (2014) pp. 339–346. https://doi.org/10.1016/J.ENGFAILANAL.2014.06.015.

[3] L. Deng, W. Wang, Y. Yu, State-of-The-Art Review on the Causes and Mechanisms of Bridge Collapse, Journal of Performance of Constructed Facilities. 30 (2016) pp. 04015005. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000731.

[4] National Transportation Safety Board, Collapse of the Interstate 5 Skagit River Bridge Following a Strike by an Oversize Combination Vehicle National Transportation Safety Board, 2013. http://www.ntsb.gov/investigations/dms.html (accessed April 12, 2023).

[5] K. Wardhana, F.C. Hadipriono, Analysis of Recent Bridge Failures in the United States, Journal of Performance of Constructed Facilities. 17 (2003) pp. 144–150. https://doi.org/10.1061/(ASCE)0887-3828(2003)17:3(144).

[6] E. Bertolesi, M. Buitrago, J.M. Adam, P.A. Calderón, Fatigue assessment of steel riveted railway bridges: Full-scale tests and analytical approach, Journal of Constructional Steel Research. 182 (2021) pp. 106664. https://doi.org/10.1016/J.JCSR.2021.106664.

[7] M. Buitrago, E. Bertolesi, P.A. Calderón, J.M. Adam, Robustness of steel truss bridges: Laboratory testing of a full-scale 21-metre bridge span, Structures. 29 (2021) pp. 691–700. https://doi.org/10.1016/j.istruc.2020.12.005.

[8] International Organization for Standardization, ISO 2394:2015 - General principles on reliability for structures, (n.d.). https://www.iso.org/standard/58036.html (accessed April 12, 2023).

[9] M. Correia, H. Perneta, M. Salta, Maintenance and repair of transport infrastructures: Part III - Steel structures, Vol 5 – Protection systems, n.d. https://www.researchgate.net/publication/268674403_DURATINET_Technical_guide_-_Maintenance_and_repair_of_transport_infrastructures_Part_III_-_Steel_structures_Vol_5_-_Protection_systems (accessed April 12, 2023).

[10] J.C. e Matos, J.R. Casas, S. Fernandes, COST Action TU1406 quality specifications for roadway

bridges (BridgeSpec), Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks. (2016) pp. 299–299. https://doi.org/10.1201/9781315207681-141.

[11] International Organization for Standardization, ISO 13824:2020 Bases for design of structures — General princi..., (n.d.). https://tienda.aenor.com/norma-iso-13824-2020-071005 (accessed April 12, 2023).

[12] Eurocode 3: Design of steel structures | Eurocodes: Building the future, (n.d.). https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-3-design-steel-structures (accessed April 12, 2023).

[13] M.H. Faber, J. Qin, S. Miraglia, S. Thöns, On the Probabilistic Characterization of Robustness and Resilience, Procedia Engineering. 198 (2017) pp. 1070–1083. https://doi.org/10.1016/J.PROENG.2017.07.151.

[14] F.C. Campbell, Fatigue and Fracture of Ceramics and Polymers, Fatigue and Fracture - Understanding the Basics. (2012) pp. 327–375.

[15] International Organization for Standardization, ISO 8044:1999(en), Corrosion of metals and alloys — Basic terms and definitions, (n.d.). https://www.iso.org/obp/ui/#iso:std:iso:8044:ed-3:v1:en (accessed April 12, 2023).

[16] S. structures-P. 1: M. and design (ISO 10721-1:1997) International Organization for Standardization, ISO 10721-1:1997 - Steel structures — Part 1: Materials and design, (n.d.). https://www.iso.org/standard/18814.html (accessed April 12, 2023).

[17] International Organization for Standardization, IEC 31010:2019 - Risk management — Risk assessment techniques, (n.d.). https://www.iso.org/standard/72140.html (accessed April 12, 2023).