v. 3, n. 11, 2023

Journal of
**Engineering
Research**

FATIGUE ASSESSMENT FOR A COMPOSITE BRIDGE IN STEEL ARCHES ACCORDING TO ABNT NBR STANDARD REQUIREMENTS: 16694:2020

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DOI 10.22533/at.ed.3173112304047

Abstract: Bridge structures, when subjected to repeated action of mobile load, present stress variations in the structural elements and that under this stress condition can cause the phenomenon of fatigue, characterized by the appearance of cracks and subsequent propagation, which can lead to the collapse of the structure. The verification of resistance to fatigue in structural projects of road bridges in straight composite beams must be carried out according to the requirements of Annex A of the ABNT NBR 16694:2020 standard, which specifies the permissible limit of the stress variation range for categories of constructive details and for a number of request cycles. The present work aims to evaluate the fatigue of the structural elements of the superstructure of a composite bridge in metallic arches in order to meet the requirements presented in Annex A of the ABNT NBR 16694:2020 standard. The composite bridge in metallic arches studied here has a deck in composite straight beams and was designed to serve the water main system of the São Francisco River and is also used as a pedestrian walkway. Initially, a finite element model was elaborated for the composite bridge structure in steel arches. Next, loadings were established for the frequent combination of fatigue. The design stress variation range was determined from tensile stress results from finite element analysis. The fatigue evaluation for the structural elements of the composite bridge in metallic arches was only carried out for the regions of the weld fillet between the web of the spar beam profile and the vertical stiffener where the initiation and propagation of cracks in this region causes the failure of the flange tension and can lead to the collapse of the beam. Thus, the permissible range of voltage variation was established for the constructive detail of the welded connection in question and according to the representation indicated in Table A.1 of Annex A of the ABNT NBR 16694:2020 standard. In the end, it was confirmed that the range of design stress variation is lower than the admissible range of stress variation and thus the composite bridge structure in steel arches is safe to fatigue.

Keywords: Mixed bridge; Fatigue check; Standard ABNT NBR 16694: 2020; Finite element analysis.

INTRODUCTION

Road bridges and walkways are subject to fatigue loading due to mobile load as established by ABNT NBR 7188:2013. The action of the mobile load crossing the span produces stress variations in the structural elements of the bridge and that under this stress condition can lead the material to suffer the phenomenon of fatigue that is characterized by the initiation and propagation of cracks and that can lead to the collapse of the bridge. bridge structure by brittle failure.

FISHER (1981, apud KLINSKY, 1999, p. 58) states that the main factors that cause the appearance of cracks due to fatigue in bridges are due to the volume of traffic, the age of the bridge, magnitude of stress variations due to mobile load, types of geometric details of the structural elements and the quality of execution of the details and the fracture toughness of the material.

According to SMITH (1989), cited by KLINSKY (1999, p. 58), in general, welded structures are more susceptible to developing the phenomenon of fatigue than structures in bolted or riveted connections; this is due to the fact that in the welding process there is the introduction of residual stresses in the material and the appearance of microcracks next to the weld bead.

Procedures for verifying fatigue in structural elements of composite bridges according to the prescriptions of the Eurocode standard are found in VAYAS (2017). VAYAS (2017) provides a theoretical explanation of fatigue verification by the SN method for constant amplitude and variable amplitude loads. It also discusses constructive details defined for welded joints, discusses some types of train models of load type used in fatigue analysis and presents simplified procedures for evaluating the fatigue of the main structural elements present in composite bridges in straight beams.

BILÉ (2009) evaluated the fatigue behavior of road and railway composite steel and concrete bridges, medium span and cross section in two spar beams and according to the types of detail categories and criteria of the Eurocode standard. He highlighted the main types of detail categories that are more conditioning for the structural design of composite bridges in two spar beams.

ZACARIAS et al (2012) developed a comparative fatigue verification study for an industrial crane rolling beam between the ABNT NBR 8800:2008 standard and the ANSI/AISC 360-10 and CSA S16-01 guides. He concluded that the vertical impact coefficient influences the stresses acting on the bearing beam, as it amplifies the moments generated by the passage of mobile loads. It also advises that the indications of the AISC 360-10 guide must be followed regarding the importance of performing full penetration welds in the connection between the web and the upper flange, and between the stiffener and the upper flange of bearing beams, in reason that these effects are often not accounted for in the calculation of fatigue assessment of bridge cranes.

LEITÃO (2013) developed a fatigue assessment by dynamic finite element analysis for a composite road bridge. In the representation of the standard train, a model consisting of mass-spring-damper systems was used. A forced vibration dynamic analysis was processed to obtain stress histories and cycle counts by the Rainflow Method. The fatigue check was made by comparing the number of service life cycles of the bridge with values of SN curves from the AASTHO and Eurocode standards.

The ABNT NBR 16694:2020 standard in its Annex A presents the necessary prescriptions to be adopted in determining the permissible limit of the voltage variation range, taking into account several categories of constructive details and for a number of request cycles, and which must be considered in the fatigue assessment for structural elements of road bridges in composite straight beams.

The present work aims to evaluate the fatigue of the structural elements of the superstructure of a composite bridge in metallic arches in order to meet the requirements presented in Annex A of the ABNT NBR 16694:2020 standard. The fatigue evaluation for the structural elements of the composite bridge in metallic arches will only be carried out for the regions of the weld fillet between the web of the spar beam profile and the vertical stiffener. This is because the stringer beams are primary structures and the initiation and propagation of cracks in these regions cause the rupture of the tensioned table and can lead to the collapse of the beam. For the development of the work, a finite element model will be elaborated for the structure of the composite bridge in metallic arches. The fatigue analysis loads were established from the frequent combination of fatigue. The design stress variation range was determined from tensile stress results from finite element analysis. The permissible range of voltage variation will be established for the constructive detail representative of the welded connection under study and as indicated in Table A.1 of Annex A of ABNT NBR 16694:2020. At the end, a fatigue assessment of the welded connection will be made in order to verify whether the value of the design stress variation range is below the value of the permissible stress variation range.

THE MIXED BRIDGE IN METALLIC ARCHES

A mixed bridge with metallic arches 200 meters long, with 4 arches measuring 50 meters, and 7.9 meters wide, illustrated in Figure 1, was designed to serve the water main system of the São Francisco River in Aracaju/Sergipe and also to be used as a footbridge.

DESCRIPTION OF THE STRUCTURAL SYSTEM OF THE MIXED BRIDGE IN METALLIC ARCHES

The structural system of the bridge is composed of metal arches in rectangular tubular profiles with a section of 1000×300×22×22 mm and with diagonal elements, uprights and transverse locks in circular metallic tubes with a section of 219.1×10 mm. The deck of the bridge is formed by a concrete slab with a thickness of 18 cm, with beams in I-profile section 500×350×9.5 mm and with transverse beams in I-profile section 300×200×7.9 mm.

Figure 2 illustrates a side and cross-sectional view of a 50 m section of the bridge.

Figure 1 – Mixed metal arched bridge for a pipeline system and use as a walkway.

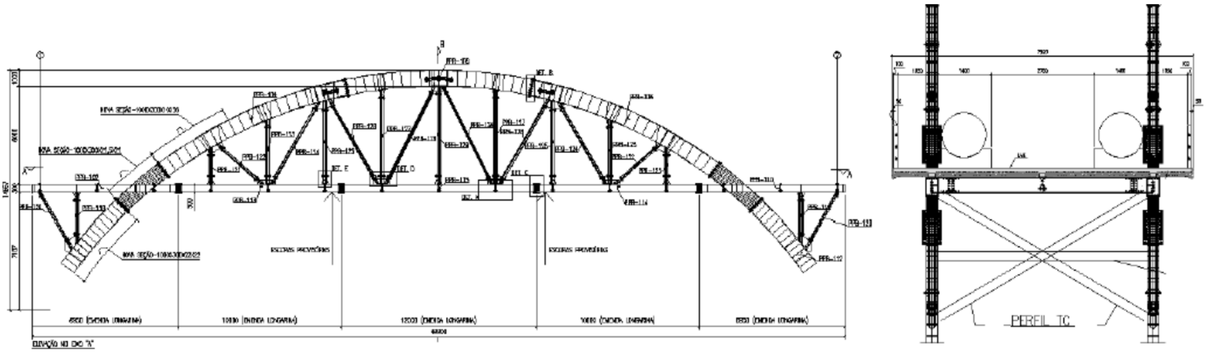


Figure 2 – Structural system of the composite bridge in metallic arches.

FINITE ELEMENT COMPUTATIONAL MODEL OF THE MIXED BRIDGE IN STEEL ARCHES

In order to evaluate the fatigue of the structural elements of the composite bridge in metallic arches, a computational model of finite elements was elaborated, as shown in Figure 3. In the modeling of the bridge, shell elements were used to model the structure of the deck slab and beam elements to model bar structures such as: arches, diagonals, uprights, transverse bracing, spar beams, transverse beams and foundation piles. The soil-structure interaction was simulated considering spring elements and spring coefficient values established by soil sounding results. The mains tubes, sleeper elements and guardrails were not modeled and their weight values were applied to the model as acting loads.

LOADS FOR FATIGUE ANALYSIS OF THE COMPOSITE BRIDGE IN STEEL ARCHES

The loads applied to the composite bridge model in metallic arches were defined by permanent actions of the structure's own weight and of permanent fixed elements (steel pipes of the mains, sleepers and guardrail structure) and by the variable action of mobile load. The variable live load action was defined only as a vertical load of 5 kN/m2 according to ABNT NBR 7188:2013, Footbridge Structures, and was applied to the finite element model in the most unfavorable position and without considering the impact coefficient vertically, as shown in Figure 4.

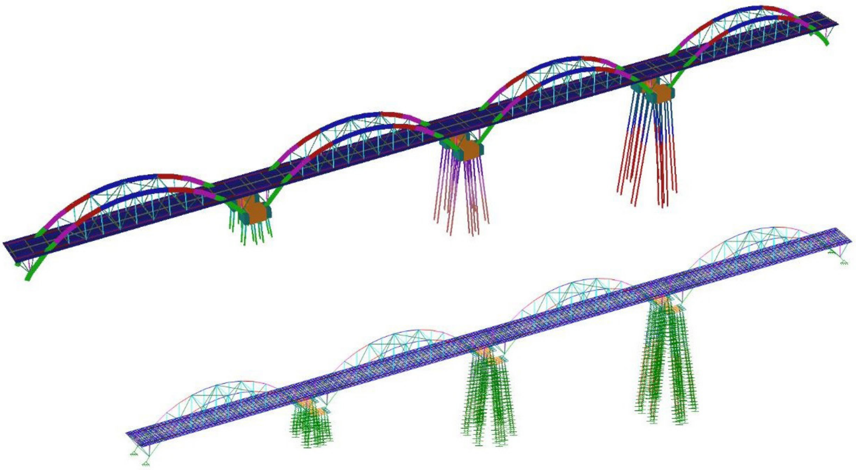


Figure 3 – Finite element model for the composite bridge in metallic arches.

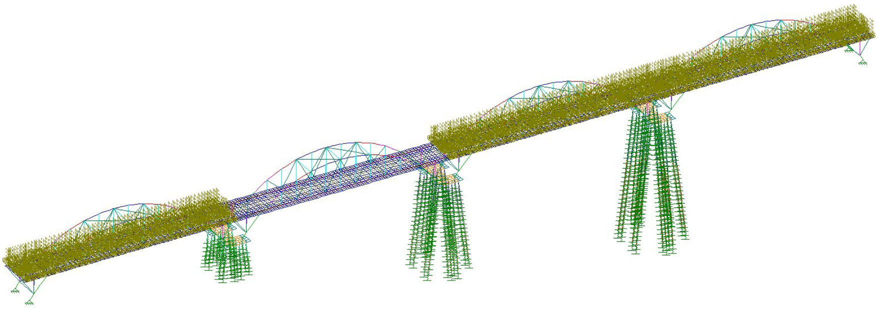


Figure 4 – Variable vertical load action in the most unfavorable position.

FATIGUE FAILURE IN WELDED STRUCTURAL ELEMENTS OF STEEL BRIDGE BEAMS

VAYAS (2017) defines fatigue as a process in which damage is accumulated in the material under the action of stress variation due to the acting load. The damage takes the form of cracks in the material that develop slowly in the early stages of loading and accelerate very quickly towards the end of the process, leading to fracture of the material. Microcracks start at stress concentration points for stress values that may be well below the elastic limit of the material. Evidently tensile stresses are more harmful to fatigue than compressive stresses. Therefore, fatigue is a local phenomenon that occurs in regions of stress concentrations such as changes in the geometric section, in bolted or welded connections, where the material undergoes metallurgical changes.

MAEDA et al (1991, apud KLINSKY, 1999, p. 58) points out that the main problem that fatigue causes in welded bridges is the appearance of cracks close to the weld sites. This way, he makes a classification for the cleft type as indicated in Figure 5.

The Type 2 Crack classification (FISHER (1981, apud KLINSKY, 1999, p. 60) indicated in Figure 5 characterizes a crack that starts at the base of the weld fillet between the beam web and the vertical stiffener and the propagation of this type of cracking causes the rupture of the tensioned table and can lead to the collapse of the beam. Thus, it appears that the critical structural element of the composite bridge in metallic arches to be evaluated for fatigue are the spar beams and for the region of the weld fillet between the web of the beam profile and the vertical stiffener as highlighted in red dashed lines in the photo of Figure 6.

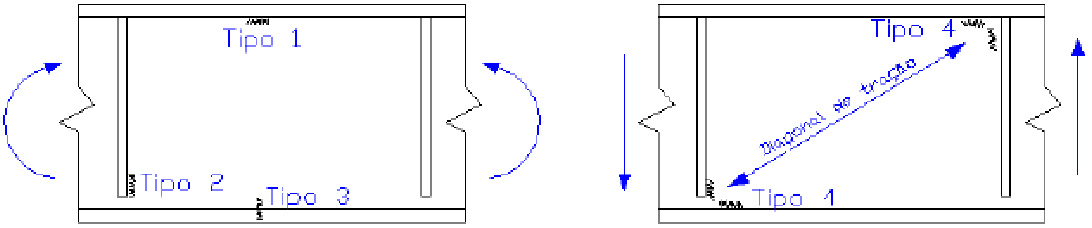


Figure 5 – Fatigue cracks observed in metallic bridges.

Figure 6 – Critical sections of the stringer beam regarding the occurrence of fatigue failures.

It is clarified that in the present work, the verification of fatigue was waived for the other structural elements of the composite bridge in metallic arches, such as: diagonal elements, uprights and transverse braces, transverse beams and metallic arches. The justification for such exemption consists in the fact that these elements are in screwed connections and also have redundancy, and in the case of metallic arches, these work predominantly in compression. It is therefore judged that the problem of the phenomenon of fatigue in these structural elements will not cause structural collapse for the composite bridge in metallic arches.

FATIGUE VERIFICATION PROCEDURE PER ABNT NBR 16694: 2020 STANDARD

Annex A of the ABNT NBR 16694:2020 standard provides the necessary prescriptions for the fatigue assessment of steel structural elements and connections for steel bridges and composite steel and concrete bridges. Such annex considers repetitive or cyclical actions, with stress variation in the elastic regime, whose frequency and magnitude are sufficient to initiate cracks and progressive collapse due to fatigue.

The Annex A considers the following frequent combination of fatigue:

$$F_{d,fad} = \sum_{i=1}^{m} F_{Gi,k} + \psi_1 \sum_{j=1}^{n} F_{Qj,k} \tag{1}$$

Where:

$F_{Gi,k}$ is the characteristic value of permanent actions;

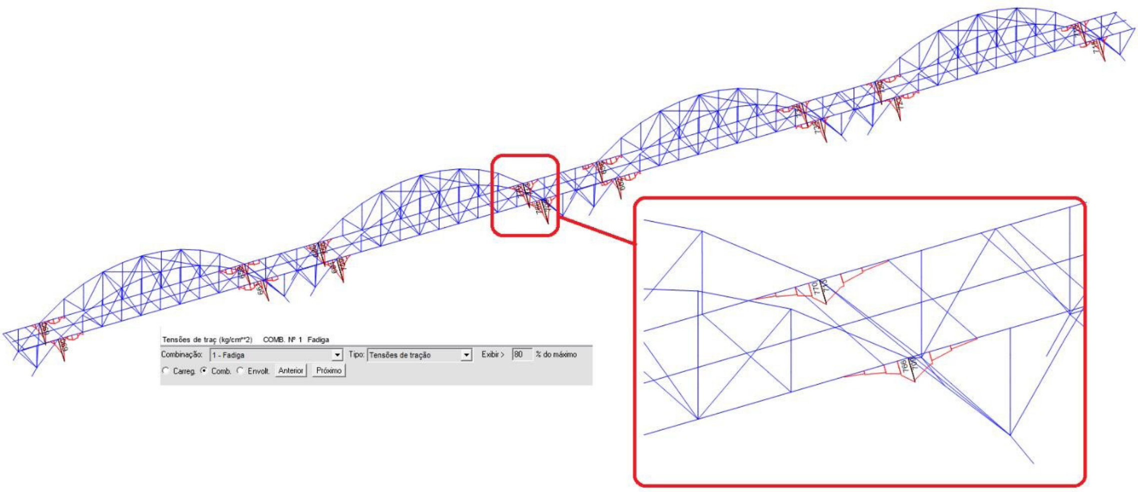
$F_{Qi,k}$ is the characteristic value of the variable actions, being, in this case, only the mobile loads;

Ψ_1 is the reduction factor for variable actions according to Table 5 of ABNT NBR 16694:2020.

In establishing the frequent combination of fatigue, the reduction factor was adopted: Ψ_1 de 0,5.

FATIGUE ASSESSMENT FOR THE STRUCTURAL ELEMENTS OF THE COMPOSITE BRIDGE IN STEEL ARCHES

Figure 7 shows the result of the maximum tensile stresses due to the frequent combination of fatigue acting on the structural elements of the spar beams.



Tensões de traç (kg/cm**2) COMB. Nº 1 Fadiga

Combinação: 1 - Fadiga

Tipo: Tensões de tração

Exibir > 80 % do máximo

○ Carreg. ● Comb. ○ Envolt.

Figure 7 – Tensile stresses (kgf/cm^2) on spar beams - Frequent combination of fatigue.

The design tensile stress due to frequent fatigue combination is 77 MPa.

For the fatigue assessment of the critical section of the stringer beam, the constructive detail of description 4.1 of Table A.1 of Annex A of the ABNT NBR 16694:2020 standard was considered and shown in Figure 8.

It is observed that the admissible range of voltage variation (σ_{TH}) is 83 MPa.

CONCLUSION

A fatigue assessment was carried out for a composite bridge in metallic arches in order to meet the requirements of Annex A of ABNT NBR 16694:2020. The fatigue assessment was only carried out for the weld fillet region between the web of the spar beam profile and the vertical stiffener. It was found that the maximum tensile stresses due to the frequent combination of fatigue was 77 MPa and was below the admissible range of stress variation of the constructive detail, which was 83 MPa. Therefore, the analyzed region will not present fatigue problems during its design lifetime.

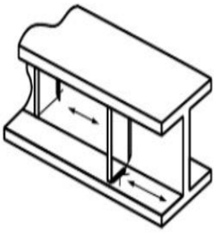
Section 4: Brazed Stiffener Fittings					
Description	**Category**	**Constant A MPa^3**	**Threshold σ_{TH} MPa**	**Potential location of fracture initiation**	**Constructive Details**
4.1 Base metal at the foot of the fillet weld between the stiffener and the table, and at the transverse fillet weld between the stiffener and the web. NOTE: It includes similar welds on contact stiffeners and connection plates.	C'	44x10^8	83	Starting at the geometric discontinuity at the foot of the fillet weld and extending into the base metal.	

Figure 8 – Permissible voltage variation range for the constructive detail of Description 4.1.

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