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SHM APPLIED TO THE REHABILITATION OF HISTORIC STEEL BRIDGE

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Abstract. The historic Imperial Dom Pedro II Bridge, located in Bahia, Brazil, underwent a major rehabilitation program that began in 2018. All tensioned diagonals, made of puddled iron, were replaced with new components, made of stronger steel. This paper presents a numerical model of the Dom Pedro II Bridge capable of reproducing structural performance before and during the replacement work. Numerical results were verified by the experimental data derived from monitoring systems installed in the bridge on several occasions. The differences observed from the numerical results could be justified by the bridge's age and maintenance condition. In general, the numerical results were fairly similar to the measured data, indicating the numerical solution could be used to assess other sequences of tensioned diagonal replacements. It was concluded that the replacement work improved the safety of the bridge, and the proposed modeling process may be suitable for other sequences of replacements, including other steel truss bridges.

Keywords: Structural health monitoring; Bridge rehabilitation; Structural impairment evaluation.

1 Introduction

Bridge deterioration is a problem in many countries, therefore rehabilitation processes are needed to preserve historical structures and extend their safe use life. Sometimes replacement of these structures is conducted, usually, due to unfeasible rehabilitation costs, as shown in Miller (1995). However, decommissioning should be a last action, since these historic bridges are part of the local community identity (Miller 1995). Hence, Bridge Management System (BMS), maintenance and rehabilitation strategies, Structural Health Monitoring (SHM), and strengthening are key procedures to maintain this historical heritage.

BMS as a systematic and organized set of activities related to planning, designing, constructing, maintaining, rehabilitating and even replacing important bridges. Several authors presented a BMS integrated to bridges 4D models having monitoring data, historical record, available funds and structural information included.

De Stefano, Matta, and Clemente (2016) detailed several case studies of historical structures in Italy, where SHM was used to improve structural understanding, evaluate any strengthening works, prevent damages or measure and control damages once a hazardous event has occurred. All these actions confirm the great value of SHM in supporting maintenance planning.

Another matter of maintenance and rehabilitation process, in old structures, is deciding which design codes should be applied, since, in general, codes were revised and changed throughout the structure life period. Sometimes comparing codes is required to a better assessment. Another issue is the required effort to rehabilitate these historic bridges, that sometimes uses unconventional solutions, such as an embedded steel truss bridge structure to restore a concrete arch bridge, as shown in Witzany and Zigler (2020).

The combination of monitoring data with numerical modelling creates an important tool that assists any decision-making on bridge management. Costa and Figueiras (2013) presented a steel bridge numerical model, which was properly validated by experimental data to evaluate the strengthening design. Building a predictive numerical model requires for mechanical and geometrical property definitions and a model complexity capable of outputting the measured experimental data in order to be adjusted.

In this paper this methodology, of joining numerical modelling with experimental data, is applied to the historic Imperial Dom Pedro II railway bridge, located in Bahia, Brazil. Which, since 2012, has been under extensive rehabilitation due to generalized corrosion and elevated stress levels at structural members, as observed in Fig 1.


(a) (b)

Fig 1. Imperial Dom Pedro II Bridge photos (a) general view (b) generalized corrosion.

Rehabilitation process included strengthening and replacement of components; in addition, various monitoring programs were installed at the bridge to assess structural health and the impact of repair tasks. The study focuses on the replacement of this bridge's tensioned diagonals which was monitored and replicated in a numerical model to simulate the structural behavior and evaluate changes in the members internal forces.

2 Bridge and model descriptions

The Dom Pedro II Bridge was constructed in 1885 over the Paragassu River. Nowadays, it is used by trains, vehicles, and pedestrian. Its four isostatic spans are made of puddled iron with a total length of 366 m, 10.20 m width and each span is 91.60 m long.

The finite element (FE) model was simplified to only one isostatic span using the software SCIA Engineer (Fig 2), in which the majority of members were represented as bar elements (1D), with six degrees of freedom (DOF's) per node; except the steel deck represented as shell elements (2D quadrilateral mesh) formulated by Mindlin hypothesis. To simulate the connection stiffness, rigid arm elements were used, hence the deformation and rotation of both linked nodes were identical.

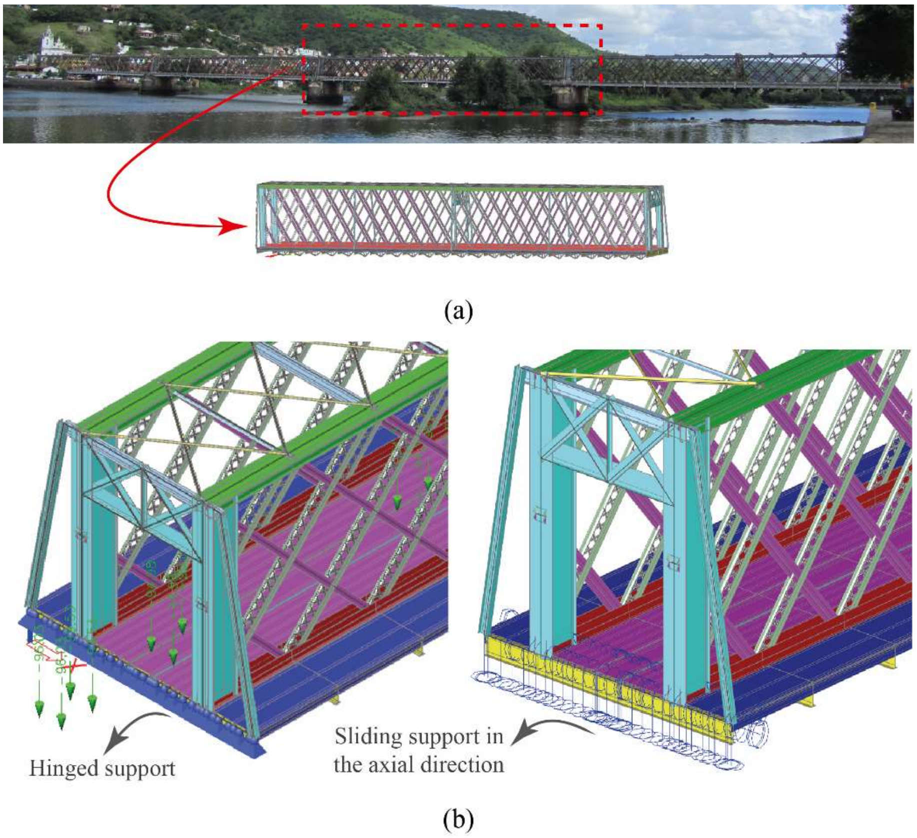


Fig 2. Numerical Model of Dom Pedro II Bridge (a) one isostatic span (b) boundary conditions.

In 2012, a short-term monitoring was installed at the bridge (Colombo et al. 2019) that measured not only strains (ε) and displacements (DV) of the structure before the replacement process, but wheel loads of a freight train, named C260 Train, as well. These parameters were used for calibrating and validating the model. In the numerical model, the train load was defined as a static load with a 10 m step to simulate the crossing, in which these measured wheel loads were defined as pointed loads. The results were similar to those monitoring data, as verified from Fig 3 and 4. Fig 3(a) shows the deformation caused by the train and indicates the sensors' location along the structure. Numerical vertical displacements at mid-span (nodes N215 and N241) caused by C260 Train are displayed in Fig 3(b) and the photo of the E26 sensor installed at the bridge diagonal is shown in Fig 3(c). As shown in Fig 4(a) the numerical graphic shape and displacement values were close to the average of the measured ones (at sensors DV2 and DV4). The relative difference between the numerical (DV_num = -59.72 mm) and average experimental (DV_exp = -59.03 mm) displacement peaks was 1.18%, showed in Fig 4(b). Therefore, this numerical model sufficiently represents the existing bridge before rehabilitation; hence it was used to simulate the diagonal replacements.

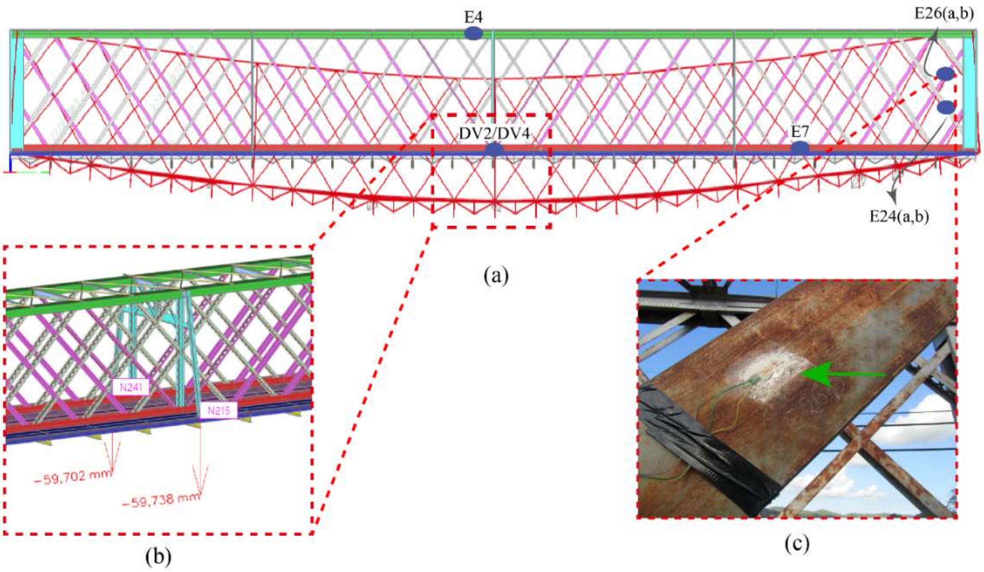


Fig 3. Short-term monitoring sensors and vertical displacement caused by C260 Train (a) sensors' location and deformed model by train crossing (b) numerical displacement at measured location and (c) E26 sensor installed.

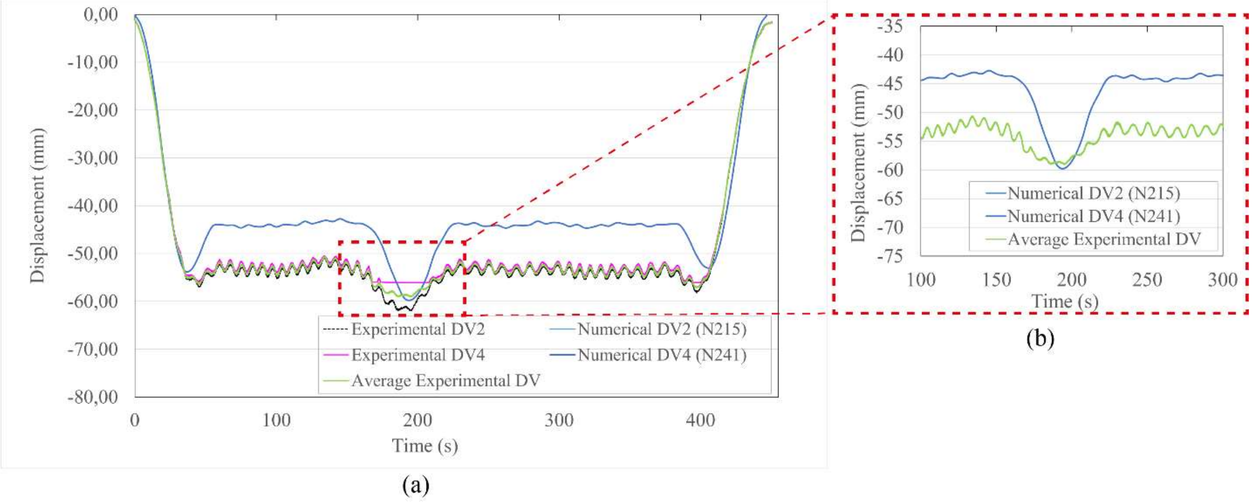


Fig 4. Curve displacement vs. time for the train crossing, (a) both experimental and numerical (b) zoom at displacement peaks.

3 Tensioned Diagonals Replacements

Dom Pedro II Bridge underwent a major strengthening from 2018 to 2019, in which a total of 352 tensioned diagonals were replaced by new components of ASTM A572 Grade 50 steel and with cross-section area greater than the old ones. The new diagonals material has a yielding stress (f_y) of 345 MPa, which is two times larger than the puddled iron. The replacement works only took place during a nocturnal period, i.e., from 9:00 pm until 05:00 am, to minimize surrounding disturbances and traffic impacts since the bridge needed to be closed during the tasks.

The chosen replacement sequence started at the mid-span towards the bearings. Both longitudinal and transversal symmetry were followed in a global scale, i.e., tensioned diagonal (T) T10 of truss A was removed, then element T10 of truss B was removed (longitudinal symmetry); afterwards, member T15 of truss A was replaced (transversal symmetry); successively. In a local scale, one bar out of the diagonal pair was removed, for example, the internal bar (i), then the new bar was installed; subsequently, the external bar (e) of that same member was replaced. Only two members were replaced per night due to the available time. In the field, the replacement of nine diagonals were monitored, such as T6e, T5i, T5e, T4i, T4e, T3i, T3e, T2e and T2i, consecutively; in addition, others tensioned diagonals (T1 and T7) and compressed diagonals (D0 to D6) were also monitored to evaluate changing in the internal forces of these closest members, as illustrated in Fig 5, that shows this methodology scheme.

The proposed methodology for replacement modelling used the software tool known as construction stage, which is used to represent any changes in a structure static system during its construction, such as, addition or removal of structural members and/or supports; variation of material Young's Modulus over time; prestressing; and gradual loading application (SCIA 2016).

In this study, the linear construction stage tool was used to simulate the bridge during its rehabilitation process; therefore, for each stage, the undeformed structured was considered. The structural members replacements were consecutively simulated as different construction stages, e.g., in one stage, the tensioned diagonal bar was removed off the structure and, in the next stage, the new component was installed in place, as illustrated in Fig 6. This process continued up to the ninth replacement (T2i) and the software automatically calculated the changes in the self-weight load that the bridge is subject to; also the internal forces for each step (SCIA 2017).

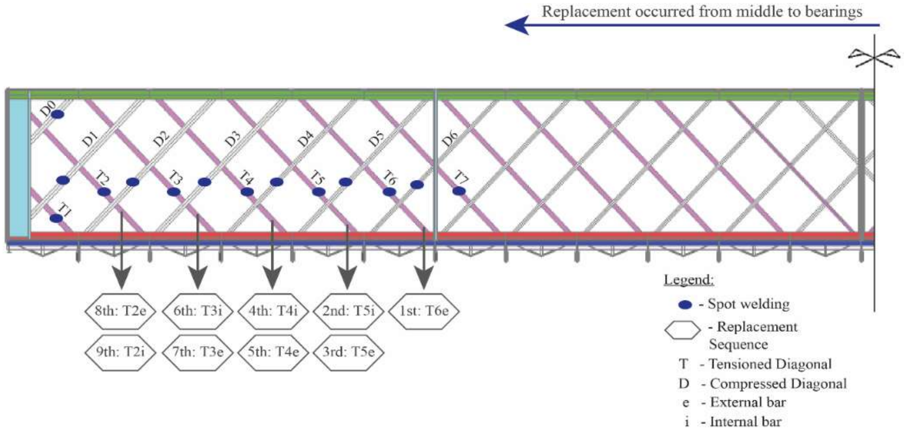


Fig 5. Scheme of the monitored tensioned diagonals replacements.

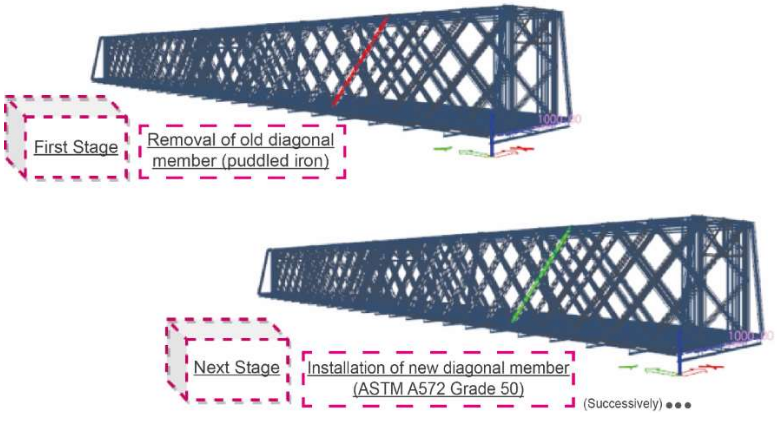


Fig 6. Scheme of the construction stages to simulate the tensioned diagonal replacements.

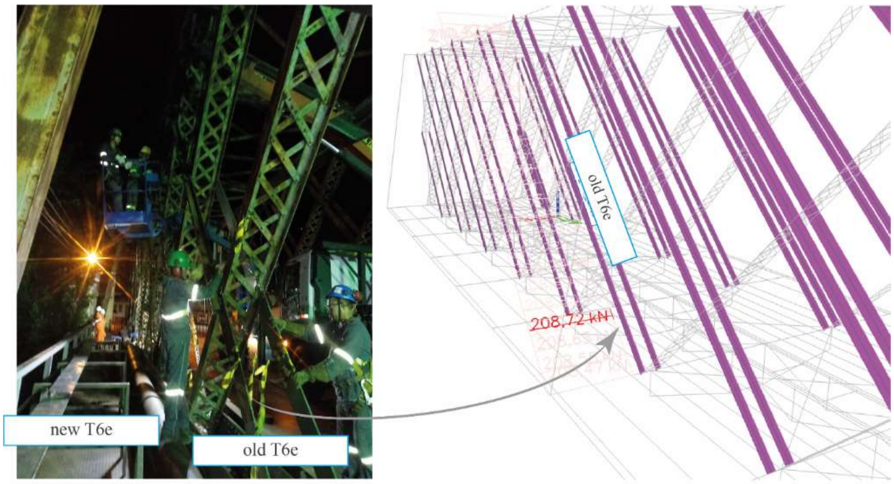
4 Results and Discussion

The result parameters were internal stress (σ) and forces (N), calculated using the measured strains, cross-sections, and material properties. The monitoring during the replacement work allowed the calculation of the exact internal forces due to permanent load of each removed tensioned diagonal right before the exchange, along with the distribution of these internal forces to the neighboring members. At each replacement stage, the new tensioned diagonal presented zero stress, until the next tensioned diagonal had been replaced.

Table 1 presents both the experimental internal force (N_exp) and the numerical force (N_num) for the nine replaced components right before the stress relief on each one of them and also, respective absolute and relative differences. Numerical forces were, on average, 57.0 kN different from the actual values collected in the bridge monitoring. The most different values corresponded to the T3e, which the numerical force doubled the experimental one. The differences could be due to the bridge's age or the elements' corrosion. Even though the numerical values exceeded the experimental ones, the model predicted well the structural behavior. Fig 7 presents the replacement work for T6e, the first monitored replaced tensioned diagonal, and the force at this component in the numerical model.

Table 1. Internal forces (N) of removed tensioned diagonal right before the extraction (replacement order).

Removed Tensioned Diagonal	**N_exp (kN)**	**N_num (kN)**	**Absolute Difference (kN)**	**Relative Difference (%)**
T6e	202.9	208.7	5.8	2.9%
T5i	204.2	189.0	-15.1	-7.4%
T5e	157.8	254.2	96.4	61.1%
T4i	226.8	238.4	11.6	5.1%
T4e	288.3	325.3	37.0	12.8%
T3i	240.8	248.9	8.1	3.4%
T3e	179.8	344.3	164.5	91.5%
T2e	349.5	272.5	-77.0	-22.0%
T2i	261.7	368.2	106.5	40.7%
		Average	**58.0**	



(a) (b)

Fig 73. T6e replacement (a) photo of the old T6e being removed (b) internal numerical force right before removal.

These axial forces were distributed over other diagonals, both tensioned and compressed elements, immediately after the force relief of each replaced member. These parcels of internal force were called Residual Force in this study. For the last monitored replacement (T2e) and for all monitored components, Residual Forces are shown in Fig 8. Both experimental Residual Forces and numerical Residual Forces are presented, besides the absolute and relative differences between these values.

Results indicate the numerical model had captured the structural behavior of the bridge during the replacement process. In general, the numerical Residual Forces were slightly lower than the experimental ones expect to the T2e force in Fig 8. In this case, the difference was up to 50 kN; however, the average absolute difference between numerical and experimental Residual Forces was 11 kN after T2e replacement. The graphics (Fig 8) also show that the complementary bar of the one replaced (i.e., the internal, if the external bar had been replaced, and vice versa) incorporated approximately 40% of the force relieved by the member removed. The numerical model indicated similar behavior, as well.

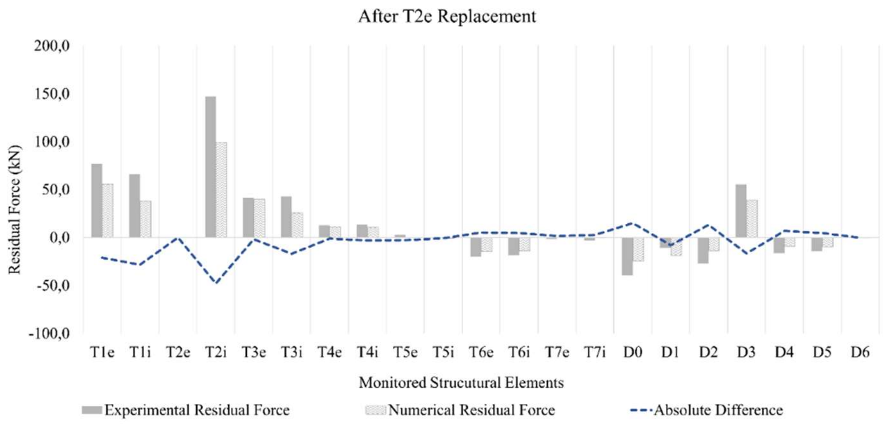


Fig 8. Residual forces of all monitored elements after t2e replacement.

5 CONCLUSION

This study presented a numerical model capable of simulating the structural behavior of the Imperial Dom Pedro II Bridge, while its tensioned diagonals were being replaced by new and stronger elements. The showed results indicate that the simplifications adopted in the modelling and neglected deterioration (corrosion) still produced suitable responses. Also, the monitoring data provided a solid baseline to the numerical model since the train wheel load values were used in the model and the strain data were reference parameters. Beam FE used in the model estimated internal forces/strains of the members quite well exempting the use of shell mesh elements, which involve more time-consuming and powerful tools. Briefly, the complexity level of the model should be careful assessed, since this study shows that the basic model combined with measured data have generated suitable results. In addition, as the complexity level increases, more difficulty could be the numerical model calibration since more parameters might affect the results.

The numerical model was able to replicates the bridge's behavior before and also during replacement work, as well. Some divergences were noticed, but they can be justified by the bridge's age and level of corrosion. In addition, the rehabilitation process applied at the bridge significantly improved the safety level of the structure, since new diagonals' material provides a higher strength. To conclude, the numerical model could be used to simulate other replacement sequences in this bridge. Similarly, the modelling methodology could be applied to other steel truss bridges that need rehabilitation works, such as consecutive replacement of diagonals components. Once the model is validated, the structural designer could suggest several solutions to rehabilitation problems, which could be costly in the field, thus, the model could contribute to define a suitable strengthening solution.

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