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Assessment of structural deformation and vibration of corrosion-damaged frame bridges under moving truck

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ABSTRACT: This paper applies a newly developed simplified dynamic finite element model that is capable to simulate individual or compound effects of traffic and corrosion loads on the dynamic performance of concrete frame bridge. The truck is modeled as a two degree of freedom dynamic system integrated with the bridge structural system in an integrated dynamic system. Corrosion-induced damage is introduced through the reduction of the reinforcing steel area, complete lose of bond in the affected zones and spalling of concrete cover. The individual and compound effects of traffic and corrosion loads have been investigated on 46.0 m frame concrete bridge through different levels of corrosion. It is found that the model is efficient in simulating the dynamic behavior of frame concrete bridge. The results highlight that the assessment of the dynamic behavior of over designed concrete frame bridge superstructure due to corrosion-induced damage could not clearly reflect critical deterioration of the bridge elements capacity.

1 INTRODUCTION

Reinforced concrete (RC) bridges in cold regions are affected by chloride-induced reinforcement corrosion from the application of de-icing salts during the cold season. Observations show that the deformations, vibrations and load capacity can be significantly reduced over time. For slab-on-girder bridges, the traffic-induced vibrations of the superstructure are reduced through dampers and discontinuity in the superstructure/substructure joints before affecting the bridge substructure. However, it is thought that the structural continuity of the frame bridge may increase its sensitivity to vibration when severe corrosion damage is induced in the super- and/or the sub- structures. On the other hand, the limited resources and the massive investments required to maintain the safety and service level of North American highway infrastructure present major challenges for owners, consultants and researchers. It is imperative to develop a quantitative infrastructure assessment approach that can help to manage public safety and being efficient and a cost. This would require a comprehensive understanding of the corrosion-related progressive damage of the structural system, the resulting deterioration of capacity and the serviceability of aging bridges subjected to the progressively developed traffic loads and volume. Major part of such an assessment is the evaluation of the change of the deformations and vibrations patterns and amplitudes of aged bridges in relation to the newly adopted design truck loads and speeds.

Frame bridge type was developed in mid twentieth century as a cost-effective and attractive alternative to the conventional arch bridge, which required massive abutments and significant excavation/grading to accommodate its relatively high profile. The strength of a concrete rigid frame bridge originated from the rigid connection of the vertical abutment walls with the horizontal deck slab, resulting in a shallow mid-span section. This bridge type has a unique ability to redistribute loads throughout the structure until it reached a balance, if any one element of the bridge is overstressed. Its immense strength and rigidity provide an additional safety to the structural system. The result is a bridge that provides greater structural strength and redundancy than reinforced concrete slab-on-girder bridges. By the 1930s and 1940s, these structures became more popular for river crossings and grade separations. Short and medium span rigid frame concrete bridges are still widely used today for rail/roadway grade separations in urban areas with constrained right-of-ways or with minimal vertical and/or horizontal clearances.

The authors developed a linear dynamic numerical model that is capable to model the individual or the compound effects of dynamic traffic load and corrosion-induced damage to RC slab on girder bridge columns (see Mohammed, et al 2010). The objective of this paper is to further generalize the mentioned dynamic model for the case of continuous rigid frame bridge. It also aims at confirming the applicability and generality of this simplified dynamic model. The bridge is modeled using two-dimensional linear finite element modeling technique, and the truck load is modeled as a two-degree of freedom dynamic system. Corrosion-induced damage is introduced through the reduction of the reinforcing steel area, complete loss of bond between the rebars and concrete in the affected zones, and spalling of the concrete covers.

2 MODELING THE BRIDGE STRCUTRUE, TRAFFIC AND CORROSION LOADS

The procedure of the numerical model proposed by the authors (see Mohammed, et al 2010 and 2013) includes two time-dependent cycles presenting each process: an external cycle that represents the corrosion process, and an internal cycle performs time-history analysis of the bridge under traffic load. More details of the linear (as well as non-linear) numerical procedures can be found in Mohammed et al. (2013 and 2010).

2.1 BRIDGE AND VEHICLE MODELS

Many attempts (Lin and Trethewey (1990), Law and Zhu (2004), Asnachinda et al. (2008), and Zambrano et al. (2008)) have been conducted to model the effects of dynamic interaction between vehicles and bridge structural systems. The truck is introduced as a two degrees-of-freedom (DOF) system integrated with the bridge structure into a unified dynamic system represented by the differential equation of motion. All the mentioned studies considered only the bridge superstructure ignoring the effects of substructure stiffness and superstructure-substructure connection on the vibration pattern and amplitude. Consequently, previous studies results have not addressed: (i) the significant effects of the traffic load on the dynamic behavior of the substructure; or (ii) the effect of the variation of substructure stiffness and the bridge structural system internal boundary conditions or continuity on the dynamic behavior of the superstructure. In this study, a frame bridge system under a moving vehicle is modeled as a two dimensional structural systems using finite element method. Three types of analysis are carried out: static analysis, free vibration dynamic analysis, and time history dynamic analysis.

A typical rigid frame bridge consists of a superstructure part connected to substructure parts with rigid joints forming a continuous structural system. This continuity between the superstructure and the substructure integrates the bridge super/substructure stiffness and effective mass to form continuous vibration waves over the whole structure when the structure is dynamically excited. The frame bridge is divided into three major beam-column parts; the horizontal part represents the superstructure, and two vertical or inclined parts represent the substructures. In order to include the effect of loss of the steel reinforcement, each part is considered as a composite section. The bridge structure is modeled using beam-column finite element with two nodes and three degrees of freedom per node, and the three parts of the structure are assembled as a two dimensional structural system . The self weight of each element is modeled as a uniform gravity load. The bridge damping matrix of the bridge is assumed linearly proportional to its mass and stiffness matrices.

The vehicle is modeled as a two degree of freedom system incorporating vertical displacement and rotation. It is assumed that the two axles of the vehicle remain in contact with the surface of the bridge superstructure throughout the truck movement and bridge deformations. Only vertical vibration is considered in this study. More detailed description of modeling the integrated/interactive truck and bridge dynamic system is provided by Mohammed et al. (2013 and 2010).

2.3 MODELING CORROSION LOAD

Reinforcement corrosion is a continuous long-term process leading to a reduction in cross sectional area of the affected steel rebars, loss of concrete section as a result of longitudinal cracking and spalling, loss of concrete confinement and possible buckling of deteriorated rebars. Corrosion damage is modeled here by calculating the reinforcement mass loss, based on Faraday's law, in addition to the loss of bar stiffness and the corresponding cross-sectional loss of the cracked concrete. The changes in the RC elements sectional properties (area and moment of inertia) lead to the variation of their stiffness and mass. Different cases of corrosion effect on longitudinal rebars and ties and hence the deterioration of stiffness and capacity are detailed in Mohammed et al. (2013a).

By applying Faraday's law, the loss of reinforcing steel due to corrosion is evaluated where the thickness reduction $x(t)$ of the reinforcing bar after time t can be calculated as $x(t) = M.i_{corr}.t/(z.F.\rho_s)$ where M is the metal molar mass (55.85 g/mol for iron), z is the valence of the ion formed as a result of iron oxidation (i.e., $z = 2$ *for* $Fe \rightarrow Fe^{2+} + 2e^-$), F is Faraday's constant (F = 96,485 C/mol), ρ_s is the density of iron (ρ_s = 7.85 g/cm^3), i_{corr} is the corrosion current density, and t is the time elapsed since corrosion started.

By substituting the values of M, z, F and ρ_s , the rate of thickness reduction results in $x(t) = 0.0116 \cdot i_{corr} \cdot t$, where $x(t)$ is given in mm, i_{corr} is given in µA/cm^2, and t is given in years. The depth of the corrosive penetration attack $p(t)$ is calculated as $p(t)=R.x(t)=R.0.0116.\ i_{corr}.t$ where R is the ratio between the maximum penetration of a pit $p_{\max}$ and average penetration p_{av} corresponding to uniform corrosion. Parameter R is also known as the pitting ratio. Val (2007) has reported that the maximum penetration of pitting on the surface of a rebar is about 4-8 times the average penetration corresponding to uniform corrosion. Assuming that the pit can be idealized as a hemisphere (Val (2007), the cross-sectional area A_s of a group of n reinforcing bars after t years of corrosion can be estimated as $A_s = (n\pi \frac{D_o^2}{4} - \sum_{i=1}^{n} A_{p,i}(t) \geq 0.0$ where D_o is the initial reinforcing bar diameter and $A_{p,i}(t)$ is the cross-sectional area of a pit after time t, which is a function of $p(t)$ and calculated according to Val (2007). It is also important to mention that the bond between the steel rebars and the concrete is assumed to be fully lost when the right before cover spalling.

3 CASE STUDY

A rigid frame concrete bridge with inclined legs built in the early 1960s is modeled as a dynamic system subjected to moving load in the following case study. The bridge consists of a single RC rigid frame bridge with central span of 28.8 m and two "overhanged" side spans of 13.71 m each. The support connections are pinned at the inclined concrete walls connection to the foundation and are rollers at the ends of "overhanged" side spans of the superstructure. The cross-section of the bridge superstructure part includes (south to north): (i) 6.096 m concrete sidewalk, 7.296 m traffic lane; (ii) 3.04 m parkway; and (iii) 6.096 m concrete sidewalk. The section of the rigid frame structure shows variable thickness of the three parts, the superstructure and two inclined walls. Figure 1 shows the longitudinal section of the structure. This frame bridge has been designed in the early sixties where the concrete compressive strength f_c of the concrete is 20MPa, and the design truck load is AASHO H20-516-44; however, in this study, the truck load used in this study has a total mass of 34,400 kg, where the body mass is 30,000 kg, the front axle mass is 2,800 kg, and rear axle mass is 1,400kg. The truck mass moment of inertia is 2.63 x 10^5 kg.m^2, the stiffness of each axle is 5,363 kN/m and the axle spacing is 6.91 m (Ali 1999). Since the dynamic model is a two dimensional (in the vertical plane of the bridge), and the variation through the bridge width perpendicular to the traffic direction (parallel the top surface of the bridge deck) is ignored, the stiffness, mass, and damping values are calculated as values per traffic lane. It should be pointed that as the design characteristics of this bridge is out of the scope of this study, the focus of this paper is only on the vibration pattern and amplitudes.

3.1 CONVERGENCE STUDY

In order to ensure the originality and accuracy of the results obtained from the proposed model of this concrete rigid frame bridge under traffic load, two convergence studies have been conducted. For both convergence studies, the truck speed is equal to 100 km/h. In the first convergence, the number of element is assumed to be fixed (NE= 88), and the number of integration joints, NI, varies from 5 to 100. Figure 2-a shows the dynamic deflection under front axle of the truck along the bridge span for different NI. It is found that after NI = 30, the change in the deflection becomes negligible. In the second convergence study, the number of integration points is constant (NI= 80), and the number of elements varies from 10 to 120. As shown in Fig. 2-b, the results become stable after NE =20 and the change in the dynamic deflection due to the increase in the number of elements becomes negligible.

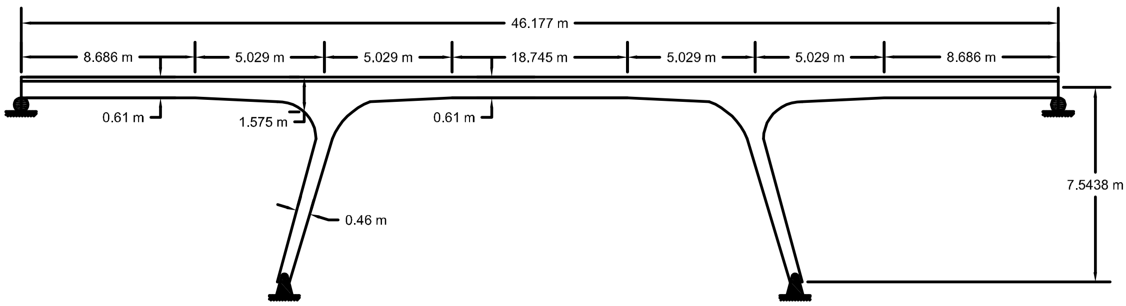

Figure 1: A rigid frame concrete bridge with inclined legs

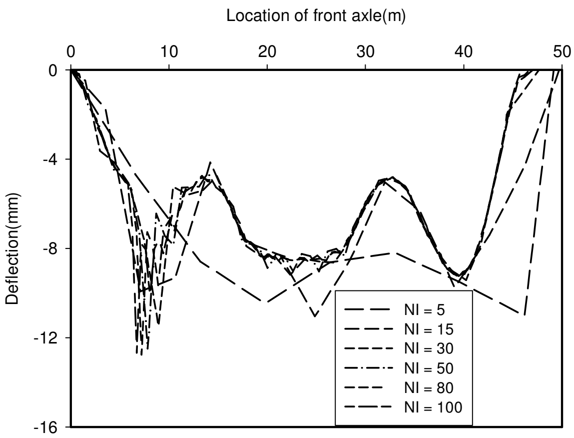

Figure 2-a: Convergence study 1: number of elements NE = 88 and truck speed = 100 km/h for different number of integration points (NI).

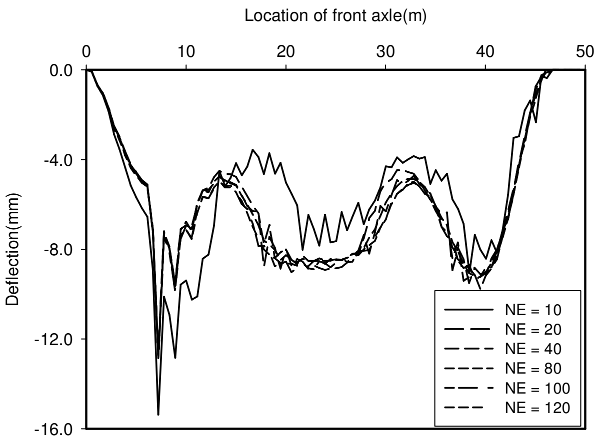

Figure2-b: Convergence study 2: number of integration NI = 80 and truck speed = 100 km/h for different number of elements (NE).

3.2 DYNAMIC DEFLECTIONS OF THE BRIDGE COMPONENTS

Integrating the results of the dynamic deformations for the vertical displacement under the truck front axle (Figure 3), and the lateral and axial displacements at the top and mid-height of the two inclined walls (Figures 4-a and 4-b respectively) gives a view of the oscillation pattern of the frame bridge system. When the truck is crossing the bridge at the maximum allowable speed of 100 km/h, the results show: (i) the two roller in the top supports allow the frame to sway horizontally; (ii) while the vertical displacement is growing downward with the movement of the truck, the left wall moves to the right side and slightly downward, the right wall moves oppositely to the left and slightly upward; (iii) the very high stiffness of the joint linking the inclined walls to the horizontal "superstructure" part reduces the vertical displacement significantly when the axles are passing over these connections; and (iv) all the figures show that sudden fluctuation and peak vibration amplitude happened when the rear axle entered the bridge, which can be explained by the high mass over the truck rear axle and the possible local dynamic excitation of the low-depth part of the superstructure at the two overhanged that results in high local oscillation. In Figure 4-a, 4-b the dynamic lateral and axial deformations of the two walls are opposite to each other, reflecting the frame mode of vibration related to its stiffness and mass distribution. Furthermore, Fig.4-a shows that the horizontal deformation of the inclined columns is maximum at connections of the horizontal-inclined columns and reduced slightly downward reaching zero at the columns supports (the pins).

3.3 BRIDGE STRUCTURE UNDER COMBINED TRAFFIC AND CORROSION LOADS

The corrosion induced damage is simulated by assuming a steel mass lose of 30 % which equivalent to 10 years of corrosion with a corrosion density of $1\mu A/cm^2$, and by assuming that the concrete cover of the substructure has spilled out, and the bond of the rebars is completely lost. Figures 5, 6-a, and 6-b show that the corrosion effects on different bridge elements does not changed the dynamic deformations patterns. A very small increases in the dynamic deformations of different parts of the frame bridge are observed as the steel area is reduced and the spalling of the concrete cover is completely occurred on the internal sides of the bridge columns only (highly exposed to splash of the melted snow). Figures 5, 6-a and 6-b show that when all the three parts of the bridge are affected from inside the frame, the vertical deflection at the mid span of the superstructure has affected the most, yet the overdesign of the bridge avoided the dramatically high increase of the dynamic deformations.

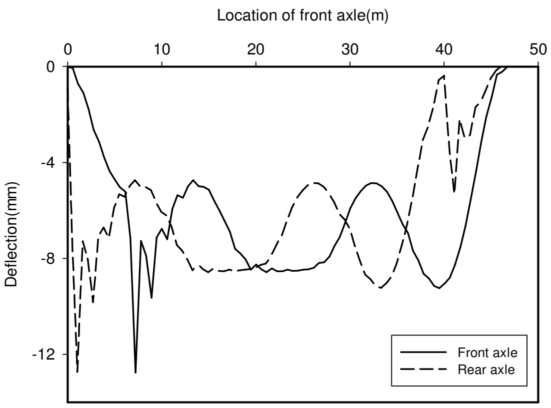

Figure 3: Dynamic deflection of the bridge superstructure under front and rear axles for a truck speed 100km/h.

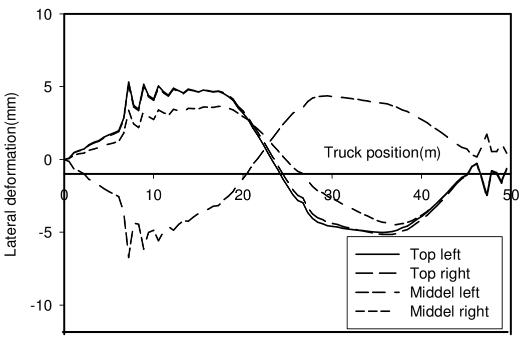

Figure 4-a: Truck position vs. maximum lateral deformation of the bridge walls.

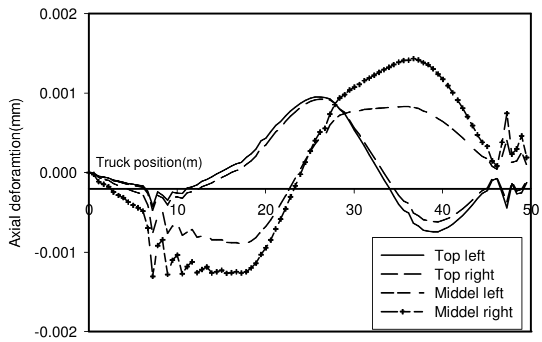

Figure 4-b: Truck position vs. maximum axial deformation of the bridge walls.

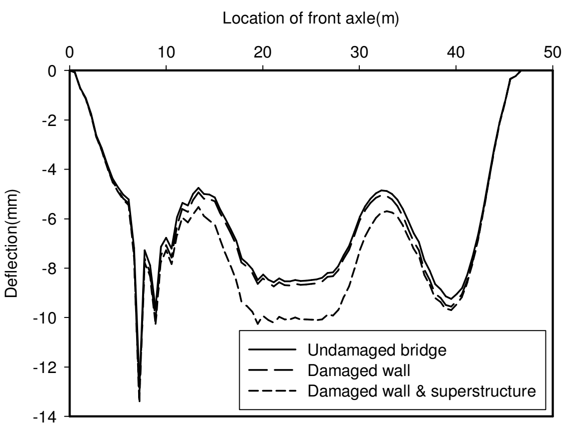

Figure 5: Dynamic deflections of superstructure under front axle for undamaged and undamaged bridge components.

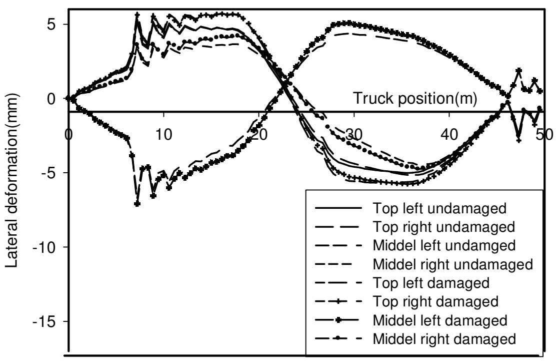

Figure 6-a: Maximum lateral deformation of undamaged and damaged bridge walls.

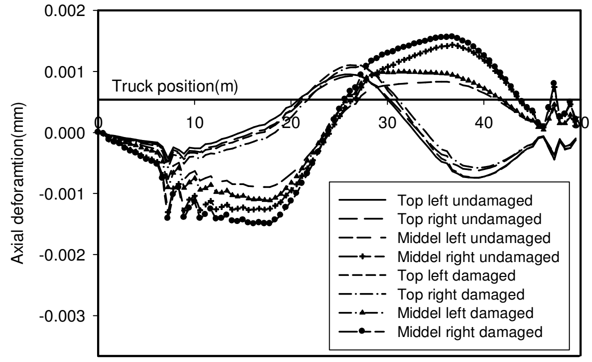

Figure 6-b: Maximum axial deformation of undamaged and damaged bridge walls.

3.4 ANALYSIS RESULTS AND DISCUSSION

It is observed that the dynamic finite element model developed by the authors is sensitive to the number of elements of the bridge superstructure and the number of integration points. In any specified application, it is required to perform convergence studies for both parameters, the number of elements and the number of integration points. It is observed that further increase of the number of elements and/or the number of integration points to a reasonably high number would not result in round-off error, which reflects the high numerical stability of the model.

Since the ratio of the steel area and ratio of the concrete cover to the bridge elements cross-sectional areas are small, then their losses are marginally affecting the elements stiffness and hence marginally affect the deformations in the elastic range. In addition, as the axial compressive stress is low and the cross sectional areas of all the bridge parts are huge, the corrosion-induced damage has not resulted in any loose of concrete confinement. In the discussed case study, it is clear that the change of the dynamic deformations of the bridge super/substructure due to the reinforcement corrosion of the super/substructure is not enough to result in significant reduction of the bridge load capacity. The bridge in the case study of this paper is way-overdesigned, where it includes massive thick slab of the horizontal or thick walls of the inclined bridge parts.

With more recent frame bridges, slender columns and superstructure are used. Such bridges could be more dynamically sensitive to the corrosion where significant change in dynamic vibration pattern and amplitude are expected. The staged deterioration of the stiffness and the material strength, lose of stirrups, lose of bond, variable mass and stiffness, local buckling of the longitudinal rebars, could result in staged change of the dynamic behavior of the bridge. In order to overcome all these nonlinear parameters, the structural assessment of the bride dynamic performance may require the use of nonlinear dynamic model.

4 SUMMARY AND CONCLUSION

For quantitative assessment of the changes in the dynamic response of concrete frame bridges when subjected to combined traffic and reinforcement corrosion, this study applies a newly developed simplified dynamic finite element model. The numerical model includes two time-dependent cycles representing the two time-processes: an external cycle, which represents the corrosion process, and an internal cycle, which performs time-history analysis of the bridge under traffic load. The truck is modeled as a two degree of freedom dynamic system integrated with the bridge structural system in an integrated dynamic system. Corrosion-induced damage is introduced through the reduction of the reinforcing steel area, complete lose of bond in the affected zones and spalling of concrete cover. The individual and compound effects of traffic and corrosion loads have been investigated on 46.0 m frame concrete bridge through different levels of corrosion.

It is found that the model is efficient in simulating the dynamic behavior of frame concrete bridge. It is capable to quantitatively assess the combined effects of the traffic load and reinforcement corrosion on the dynamic deformations. From the case study, it is found that the corrosion of the frame bridge elements results in a marginal increase of the bridge super/substructure dynamic deflection under truck movement. The model is able to capture the local dynamic excitation and oscillations results from the high variation of the stiffness and mass of the bridge superstructure. The results highlight that the assessment of the dynamic behavior of over designed concrete frame bridge superstructure due to corrosion-induced damage could not clearly reflect critical deterioration of the bridge elements capacity.

5 FUTURE WORK

The nonlinear analysis of frame bridges with slender components (columns and beam-slab systems) or more slender rigid slab/abutment frame bridge is of high importance in future work. It should be capable to identify critical failure mechanisms in relation to the dynamic performance of corrosion damaged RC frame bridges. On the other hand, through field investigations have to be performed to collect enough data that enables full calibrations of the model.

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