Effect of Reinforcement Corrosion on Safety and Stability of Slab-on-Girder Bridges versus Frame Bridges

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Abstract Chloride-induced reinforcement corrosion from the application of de-icing salts during the cold season is the major cause of reinforced concrete bridge deteriorations in cold regions. Observations show that the deformations, vibrations and load capacity of the bridge components can be significantly affected over time due to the corrosion damage of reinforcing steel and concrete. Evaluation of the residual capacity and stability of the bridge elements and the possibility of sudden failure is of significant importance for the bridge owners and practicing engineers. In this paper, the effects of the corrosion damage on the safety and the stability of slab-on-girder and frame bridges are investigated using a simplified dynamic finite element analysis. Two case studies on slab-on-girder bridge and frame bridges are investigated. It is found that when the bridge components are subjected to severe corrosion damage and their safety and stability are critical, the changes in the bridge dynamic performance parameters are marginal. However, the corrosion of the bridge superstructure results in an increase in its dynamic deflection under truck load. It is found that marginal changes in the dynamic characteristics of bridge superstructure due to corrosion-induced local damages could not indicate the criticality of the reduction of the ultimate capacity. In order to assess the bridge performance, its safety and serviceability, all the three evaluation-limit states should be quantified.

1 Introduction

Chloride-induced reinforcement corrosion from the application of de-icing salts during the cold season is the major cause of reinforced concrete bridge deteriorations in cold regions. Observations show that the deformations, vibrations and load capacity of the bridge components can be significantly affected over time due to the corrosion damage of reinforcing steel and concrete.

Among the most popular short span bridge types in North America are the slab-on-girder and frame bridges, where their structural performances when subjected to corrosion damage are of high interest. While the slab-on-girder bridges have the benefits of simplicity in design, fast in construction, they have no redundancy in the traffic direction and limited redundancy in the lateral direction. On the other hand, frame bridges have the ability to redistribute loads through the structural system until it reaches a balance when any element of the bridge is overstressed. Its immense strength, high redundancy and rigidity provided additional safety to the bridge structure. However, they have many disadvantages such as construction complexity, high construction cost, and the difficulty in evaluating their structural performance when attacked by reinforcement corrosion or material deficiency.

For slab-on-girder bridges, the traffic-induced vibrations of the superstructure are reduced through dampers. 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.

Corrosion-related damages to bridge substructures could result in significant reduction in their structural capacities and safety. However, it is not reported whether the changes in bridges substructures (columns) capacity to a critical level result in a similar critical change in the dynamic characteristics of the bridge superstructure under traffic load. On the other hand, many observations of the change of vibration amplitude of the bridge superstructure related to reinforcement corrosion of the deck slab or girders or both are reported [1].

Evaluation of the residual capacity and stability of the bridge elements and the possibility of sudden failure is of significant importance for the bridge owners and practicing engineers. 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.

The objective of this paper is to study the effects of the corrosion damage on the safety and the stability of slab-on-girder bridges and frame bridges. This comparative study enables a better evaluation of the residual capacity of both type bridges for different stages of deteriorations. The paper briefly overviews an innovative simplified non-linear finite element model capable that is employed to explore the structural performance of both type damaged bridges. A parametric study is shown through a case study on each of the two type bridges.

2 Simplified Dynamic Finite Element Analysis of Bridges

Figure 1 shows the flowchart of the simplified dynamic finite element analysis approach (SDFEA) proposed by the Authors (see [2]). The model involves both the static and the linear/nonlinear time history analyses of traffic load to be performed. The SDFEA procedure employs a non-linear time-history analysis of the bridge under traffic load, where the stiffness, mass and damping matrices of the bridge elements are successively updated at each truck new location. As the truck moves, the loads on the bridge components vary, and hence the material properties in the damaged and no-damage zones of the bridge components also vary. It is assumed that at each truck location, a static analysis is performed on the bridge components to estimate the element stiffness and mass, and hence estimate the damping as it is assumed proportional to the stiffness and the mass. The instantaneous global dynamic matrices are then assembled into the equation of motion in every integration step of the time history analysis.

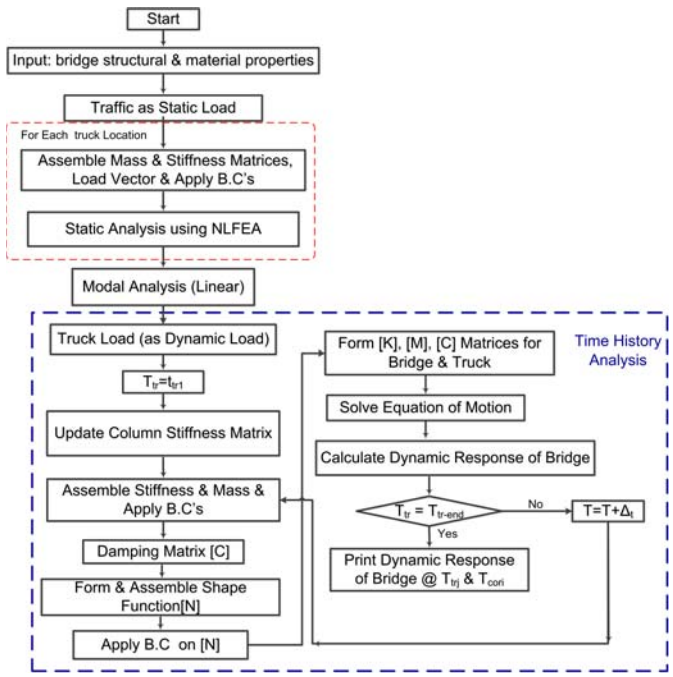

Figure 1: Simplified dynamic analysis of bridge structures under traffic load

2.1 Modelling the bridge structure

A typical slab-on-girder bridge is simply supported on columns (piers) or abutments, and they are modelled as one structural system in this study. The SDFEA is required to integrate the two components of the slab-on-girder bridge introducing an internal hinge on one side and an internal an internal roller on the other side. Since there is no load or expected response/deformation in the bridge lateral direction, the bridge structure can be modelled as a two-dimensional frame. The frame in the SDFEA is formed of a beam, representing the superstructure, and two columns representing the substructure. The connections between the beam and the columns are represented by an "internal" hinge on one side of the beam and an "internal" roller on the other side. The model also accounts for any possible eccentricity in both connections. The bases of the two columns are assumed fully fixed. The columns sections are considered as reinforced concrete “composite” sections for the purpose of the nonlinear analysis. The sectional rigidities that lead to the estimation of elements stiffness, mass and damping matrices of the corrosion-damaged columns are formulated using the nonlinear sectional analysis and the nonlinear finite element analysis (NLFEA) approaches proposed by [3]. The superstructure is formed from either slab-on-steel girders or slab-on-prestressed concrete girders. The slab is assumed to be compositely integrated to the girders. The distribution of the traffic loads (truck or lane load) in the lateral direction is assumed to follow the CHBDC load distribution approach.

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.

In the proposed SDFEA, the composite beam and the columns are modelled as two-node frame elements with three degrees of freedom at each node. The self-weight of the bridge elements is included as a uniform load. The instantaneous damping matrices are derived assuming that the damping is linearly proportional to the elements mass and stiffness.

2.2 Modelling the vehicle

A description of modelling the integrated/interactive truck and bridge dynamic system is provided by [2], where the vehicle is modelled 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.

2.3 Modelling the corrosion load

Reinforcement corrosion is a continuous long-term process, leading to reduction in cross-sectional area of the affected steel bars, loss of concrete section as a result of longitudinal cracking and spalling [4], and the local bond loss of tensile steel reinforcement. Hence, reinforcement corrosion may cause significant changes in the bridge elements capacity and safety. However, it is very challenging to develop practical time-dependent analytical models that are capable to accurately estimate the effects of different reinforcement corrosion scenarios on the structural behaviour of damaged RC elements.

In this study, a detailed measurement of the damaged zones together with any required material testing are prepared for the SDFEA. This can be performed as part of an enhanced inspection of the aged bridge elements (see [5]). If the material tests are not the option in some cases or only limited corrosion parameters need to be evaluated, then empirical formulae are used. In such formulae the uniform rate of corrosion is assumed and the instantaneous material properties can then be estimated matching the observed level of damage.

3. Case studies

Two bridges have been selected for this study. The first bridge (Bridge I) is a slab-on-prestressed concrete girder bridge with centre to centre span of 39 m. Table 1 shows more details of the bridge superstructure. The design details of the substructure and its present state are not available, and hence it is designed for the purpose of this study based on the traditional material properties of bridge construction in the 1970's. The bridge is highway bridge with design traffic speed of 100 km/hr. The concrete compressive strength is assumed equal to 40 MPa. The substructure is assumed to be constructed from eight 400 x 400 mm^2 columns with a total height of 6 m. The columns are assumed to be joined from the top by a cap beam normal to the direction of the traffic.

Table 1: General properties of slab-on-prestressed girder bridges (Bridge I)[5,6]

Year Built	Skew Angel °	Span Length m	Girder Spacing m	Girder Properties A m^2	I m^4	H m	Trans width m	Slab thick-ness m	No. of Girder
1973	0.0	39.35	2.37	0.7	0.31	1.83	13.65	0.2	6

The second bridge (Bridge II) is a rigid frame concrete bridge with inclined legs built in the early 1960s is modelled 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 2 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.

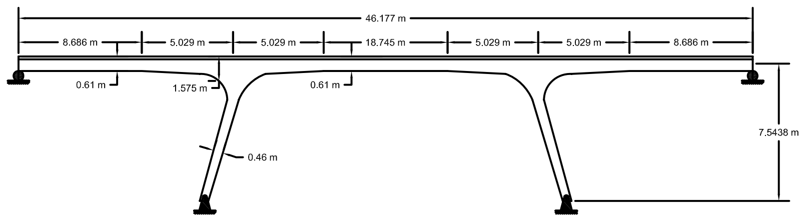

Figure 2: A rigid frame concrete bridge with inclined legs

The two present case studies involve studying the structural dynamic performance when the bridge is subjected to a two-axle truck of a total mass of 34,400 kg, where the body mass is 30,189 kg, the front axle mass is 2,806 kg, and the rear axle mass is 1,403 kg. The truck mass moment of inertia is 263,052 kg.m^2, the stiffness of each axle is 5,363,163 N/m and the axle spacing is 6.19 m (Ali 1999). Since the proposed model is a two-dimensional model and the variation through the bridge width perpendicular to the traffic direction is ignored, the reported results are based on stiffness, mass, and damping that are calculated for 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 Bridge structure under combined traffic and corrosion:

For Bridge I, four possible corrosion damage states that can be observed by visual inspection are identified in both case studies, where corrosion-induced damage is estimated assuming a steel mass loss of 30%, a corrosion current density of 1µA/cm^2; (i) a severe state of the columns reinforcement corrosion is assumed, 4 m from the base as a damage first scenario, where the concrete cover of the columns has spalled out in addition to local lose of the lateral reinforcement; (ii) 20% of the concrete cover of the middle bridge deck slab thickness has spalled out due to corrosion-induced damage (20 % CMSC); (iii) 50% of the concrete cover of the middle bridge deck slab thickness has spalled out due to corrosion-induced damage (50% CMSC); and (iv) a severe state of the columns reinforcement corrosion and 50% of the concrete cover of the middle bridge deck slab thickness (50% CMSC) are assumed as worst scenario for locations of corrosion zones. The girders are assumed less affected and damaged by the corrosion and hence there are no changes in their stiffness and mass.

Figure 3-a shows that the dynamic deflection of the bridge superstructure: (i) due to 20% CMSC is slightly higher than that when only the columns are

damaged; (ii) due to 50% CMSC are significantly increased; and (iii) with the worst scenario: when the columns have extreme corrosion damage in addition to the 50% CMSC, the dynamic deflection of the bridge superstructure have not shown any change compared to case (ii). Figure 3-b shows that the axial deformation of the right bridge column is slightly increased when the deck is damaged by 20% CMSC, and further change in deformation is observed when the deck damage is 50% CMSC.

Similar to Bridge I, the corrosion induced damage for Bridge II is simulated by assuming a steel mass lose of 30 % which equivalent to 10 years of corrosion with a corrosion density of 1µA/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 4-a, and 4-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 4-a and 4-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.

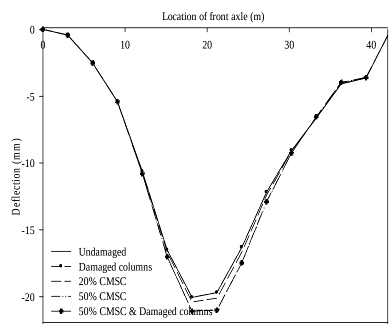

Figure 3-a: Comparison of super-structure dynamic deflections under front axle (Bridge I)

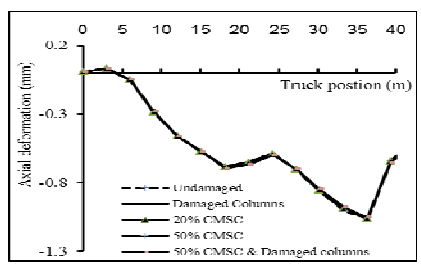

Figure 3-b: Comparison of maximum axial deformations of right column for different damage cases (Bridge I)

3.3 Static versus dynamic behaviour of bridge components

The nonlinear static behaviour of the columns when loaded up to ultimate static load and their nonlinear dynamic behaviour when they are loaded dynamically by a moving truck (traffic load) are investigated. The columns are assumed to be exposed to a severe level of corrosion damage, where the concrete cover of the columns has spalled out in addition to local loss of the lateral reinforcement (stirrups or ties). This investigation is to explore whether safety critical damage of the columns due to reinforcement corrosion can be captured by the change of any of the bridge dynamic parameters that are easy to observed and measured. Hence, it would be possible to develop a sensing technique that can predict the critical safety and stability states from the characteristic changes of the bridge dynamic behaviour (mainly displacement) under traffic.

Figures 5-a shows the load versus axial deformation for the columns of Bridge I. The load capacity is decreased and the ductility is increased when the columns are loaded to failure while they are damaged due to severe reinforcement corrosion. Figure 5-b shows the distribution of the static axial displacement, over the column height for the slab-on-steel girder bridge. It is clear that there is a change of the location of the maximum displacement when the columns are subjected to severe reinforcement corrosion. It is important to mention that the bents (or kinks) of the axial displacement distribution over the damaged-column height in Figure 5-b are located at the end of the corrosion damaged zone (4m from the base). The column boundary conditions, the reduction of axial stiffness due to corrosion damage, and the location of the damaged zone contributed to this change in the axial displacement.

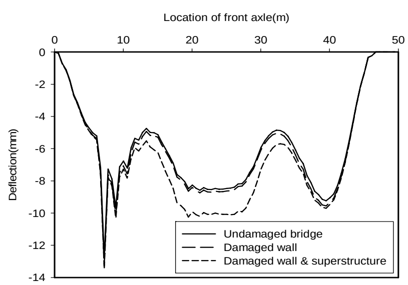

Figure 4-a: Dynamic deflections of superstructure under front axle for undamaged and undamaged bridge components.

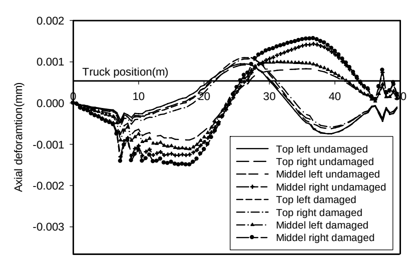

Figure 4-b: Maximum axial deformation of undamaged and damaged bridge walls (substructures).

On the other hand, and for Bridge II, 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 bridge (Bridge II), 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 II is way-overdesigned, where it includes massive thick slab of the horizontal or thick walls of the inclined bridge parts.

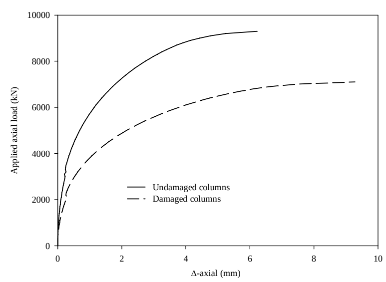

Figure 5-a: Applied axial load versus axial displacement of column top section (right before failure load); Bridge I

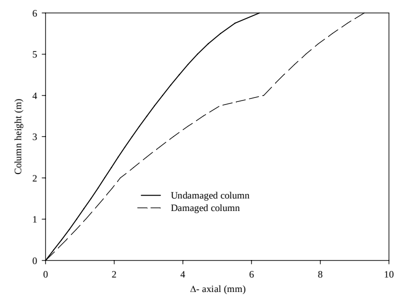

Figure 5-b: Column height versus axial displacement of the bridge column at failure load; Bridge I

4. Evaluation of the residual capacity and stability of the bridge elements

For both case studies, it should be mentioned that the service (or traffic) load magnitude is well below the ultimate static capacity of the columns, and hence even with severe local corrosion damage in the columns, their behaviours remain in the elastic or in the early plastic range. This may explain the low sensitivity of the dynamic parameters of the bridge structures to the corrosion damage of the columns, in spite of the fact that they could be in a state of critical safety and stability. Also, it should be pointed out that the results do not reflect significant changes in the dynamic behaviour of slab-on-girder bridge superstructure due to corrosion-induced damage and hence they could not quantitatively correlated to the ultimate capacity of the deteriorated critical components of the bridge.

On the other hand, 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. It should be capable to identify critical failure mechanisms in relation to the dynamic performance of corrosion damaged RC frame bridges. This may affect the residual capacity and stability of the bridge elements due to the possibility of sudden failure.

5. Conclusion

From the case studies, it is found that while bridge columns are subjected to severe corrosion damage and their safety and stability are critical, the changes in the bridge dynamic performance parameters are marginal. However, the corrosion of the bridge superstructure results in an increase of its dynamic deflection under truck load, and marginal effects on the dynamic performance of the bridge columns.

Since the bridge columns are typically overdesigned and hence the truck loads are well below the ultimate static design capacity of these columns, then even with severe local corrosion damage in the columns, their behaviours remain in the elastic range. This can explains the marginal changes in the deformations of locally corrosion damaged columns. The results highlight that the marginal changes in the dynamic characteristics of the bridge superstructure due to corrosion-induced local damages could not reflect how critical the reduction of the ultimate capacity is. In order to assess the bridge performance, its safety and serviceability, it is required to check all the three evaluation-limit states (evaluation ultimate limit state E-ULS, evaluation earthquake limit state E-ELS and evaluation serviceability limit state E-SLS).

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