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INFLUENCE OF MOVING LOADS ON CURVED BRIDGES

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ABSTRACT
The behavior of a curved slab bridge decks with uniform thickness under moving load is investigated in this study. Three radii of curvature "R" are used (25, 50 and 75m) along with the straight bridge, $R = \infty$. The decks are simply supported or clamped along the radial edges and free at the circular edges. The AASHTO[1] standard axle load of the truck H20-44 is used and assumed to move in three track positions on the bridge. The finite element method is employed for the analysis and the ANSYS 5.4 computer program is used for modelling and solving the cases studied. Six different velocities (with a time required to pass the bridge ranging from 0.4 to 2.4 of the natural period of the bridge) are used to investigate the velocity effect of the selected truck on the behavior of the bridge. All the results obtained (stresses and vertical displacements) at mid-span are normalized to the corresponding results of the static load. Results show that the maximum effect reached when the load crossing the bridge in a time (66% to 80%) of the natural period of the bridge. The increase in central displacement due to a combined effect of curvature and velocity is up to 1.75 times the static displacement, while a higher increase obtained for shear stresses.

KEYWORDS: curved Bridge, moving load, finite element, AASHTO standard load, load velocity effect, ANSYS program.

INTRODUCTION
Horizontally curved bridges are commonly used in highway interchange areas. The increase in usage of such structures is due to economical, aesthetical, architectural and engineering limitations. Bridge structures have been mainly designed to prevent failure under static loads. The static response of bridge structure can be obtained quite satisfactorily by different analysis techniques. The dynamic response of bridges due to moving loads is not easy to predict. Most of existing design codes, such as AASHTO, take the dynamic effect into account by increasing the static design loads by an impact factor "I", which is a function of span length only[1,2]. Different studied cases on bridge's dynamic response showed that the real dynamic effect differs from that obtained by multiplying the static effect by a dynamic impact factor "I" [8].

The dynamic study of bridge-vehicle interaction has been conducted theoretically and experimentally for many years due to its importance and difficulty. The existence of moving mass makes the problem more difficult because of the fact that acting forces varies in time and space. The investigation of this problem results in a large number of publications.

Dey and Balascbramanian (1982) [10], investigated the dynamic response of horizontally curved bridge decks with orthotropic elastic properties and simply supported along the radial edges under the action of a moving vehicle by using a finite strip method. Dynamic deflections and moments were presented for the mid-point of the bridge deck.

Lee, Duen, and Chung (1987)[12] ,carried out both static and dynamic tests on an old reinforced concrete bridge prior to its demolition. The purpose of the static test was to calibrate the mathematical model used in the structural analysis. The revised mathematical model was used to calculate the natural frequencies of the bridge deck. The results compared reasonably well with the measured frequencies from the dynamic test. The study demonstrated that within the design load range, the moment of inertia of a reinforced concrete bridge deck can be taken as that

of the plain concrete section. The effect of steel reinforcement and concrete cracking tend to compensate each other and may therefore be ignored.

Austin and Lin (1996) [4] ,used three-dimensional finite element model to analyze a two-span highway bridge with one end hinged support and the other end roller support. The influence line of mid-span displacements caused by a 1000kip concentrated moving load along the outer girders was computed.

Barefoot et al (1997) [5], investigated the validation of the finite element models by ANSYS 5 program to predict the static and dynamic response of steel girder bridges through comparison with field test data of a typical bridge. A well accepted comparable results were obtained.

Challal and Shahawy (1998)[7], provided a state of the art review on dynamic testing procedure for bridges with special emphasis on experimental evaluation of the dynamic amplification factor (DAF). The evaluation of (DAF) was also provided in terms of different parameters like fundamental frequency, damping characteristics of the bridge, road way roughness, vehicle speed, bridge geometry, construction materials and wheel dynamic load measurement. Very stiff bridges were more influenced by vehicle mechanical properties than most modern less stiff highway bridges.

Broquet (1999) [6], describes a parametric study to investigate the distribution of the dynamic amplification factors throughout a bridge deck slab, based on the simulation of bridge-vehicle interaction. A three dimensional finite element model was employed to represent the bridge structure. And the vehicle was represented by a system of lumped masses. For the simulation of the dynamic effects, vehicle speed was varied between 40 and 120 km/h. with trajectories either centered on, or at the edge of the deck slab. The dynamic amplification factor was higher in the first span of a continuous bridge. An increase in vehicle weights led to a decrease in (DAF).

Martin et al (2000)[13], developed a finite element model of a typical bridge structure by using ANSYS program. The relative influence of various design and load parameters was investigated using element model of a section of an actual bridge. Mid-span displacement of the bridge was calculated and normalized with respect to the static displacement. The most important factors affecting dynamic response were the basic flexibility of the structure and more specifically, the relationship between the natural frequency of the structure and the exciting frequency of the vehicle.

Jawad (2005) [11], studied the dynamic behavior of concrete bridge decks due to moving vehicles. Three dimensional models of bridge decks were implemented within the finite element method using ANSYS 5.4 computer program. Dynamic amplification factors were evaluated at certain locations on the bridge for vertical displacement, normal stress in longitudinal direction and shear stress in the transverse direction. Numerical results showed a general trend for higher values than those specified by the AASHTO design code.

Dakheel (2007) [9], used the finite element method and thin plate theory to analyze a skew bridges (with different skew angles) subjected to moving loads. The bridges structures were modeled using ANSYS 5.4 computer program. The effects of single and dual wheel loads were studied by taking different load velocities. It was found that increasing the skew angle of the bridge lead to reduction in the calculated deflection and bending stresses and increase in the shear stresses. Increasing load speed resulted in increasing the dynamic amplification factor (DAF). In the current research, the thin plate theory is employed to represent the curved bridge deck and analyzed for the effect of the variation of the truck load in location and speed on the deflection and stresses of the bridge deck.

FINITE ELEMENT MODELING
The bridge deck is simulated by using the shell 93 element which is an eight nodes quadrilateral shell element with both bending and membrane capabilities [2]. The element has six degrees of freedom at each node: translations in nodal x, y, and z directions and rotations about the nodal x, y, and z axes. The H20-44, truck design loading contained in the Standard American Association of State Highway and Transportation Officials (AASHTO) specification is used to simulate the moving vehicle. It represents two axels truck with total weight of 20 U.S. tones (180 kN)[1]. The front axle is assumed to carry 20% of the weight and the rear axle the remaining 80%. The truck and its configuration are shown in figure 1.
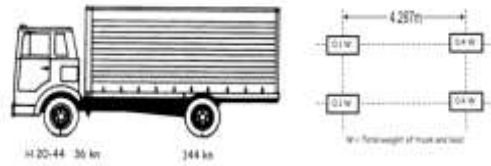
Figure (1): H20-44 AASHTO standard truck.

A programming capability in ANSYS called (the parametric design language) is implemented to simulate the load movement from node to the next node.

CASES STUDIED
The dynamic response of curved bridges with different radii of curvatures (R= 25, 50, and 75m) are studied. The plan view of the bridge is shown in figure (2). To investigate the effects of curvature on the displacements and stresses in the bridge, the resulted displacements and stresses from the analyses of the curved bridges are compared to those of a right bridge having similar width and central length. Also, two cases of boundary conditions are considered (simply supported or fixed) on both radial sides while the other sides are free. Moving axle load is applied in the study with different velocities (V) and track positions to evaluate the effect of these parameters on the results (displacements and stresses). The velocities are ranged between 20km/h to 120km/h (V/V_f = 0.4 to 2.5 where V is the velocity of the vehicle and V_f is the velocity of the vehicle when crossing the bridge in a time equals to the bridge natural period) , the track positions are as shown in figure (3).
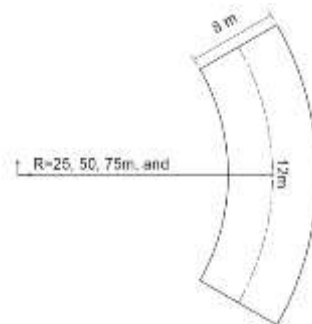
Figure 2: Plan view of curved bridge.

1- At the inner quarter line (2m from and parallel to the center line of the curved bridge.
2- At the center line of the curved bridge.
3- At the outer quarter line (2m from and parallel to the center line of the curved bridge).

   All results are normalized to those of static load (applied at mid-span, same track) to evaluate the effect of velocities of the load on the bridge at five points lie on the mid-span of the curved bridge, denoted by P_i where i=1, 2,3,4,5 as shown in figure (3).

Figure 3: Positions of a- load tracks, b- points where the effects (displacements and stresses) are calculated.
The material properties used for the bridge slab in the analysis are listed in Table 1.

Table (1): Properties of the material of the bridge

Property	Value
Density of concrete	2380kg/m^3
Modulus of elasticity of concrete (based on the ACI formula $E_c = 4730\sqrt{f'}$ for normal weight concrete)	21.52x10^3 MPa
Poisson's ratio	0.25
Damping ratio	2%

ANALYSIS AND RESULTS

To predict the effects of thickness on the response of the bridge, three thickness of the bridge slab are studied (40cm, 60cm, and 80cm) which resulted in a thickness to length ratios of (0.033, 0.05, and 0.066).

The analysis implemented in three steps, in the first step the load is applied statically to evaluate the static effect at mid-span. In the second step, the modal analysis of the structure is conducted to evaluate the fundamental natural periods and use them for the third step. The third step is done by applying the moving loads on the bridge.

The fundamental periods (T_f) and the velocity of the axel load (V_f) that would pass the bridge in time T_f for the slab with thickness 40cm are listed in Table 2.

*Table (2): Fundamental periods for bridge models, plate thickness = 40cm. simply supported bridge.*

| Radius (m)	Fundamental period T_f (sec.)	Velocity V_f km/h
25	0.9	47.92
50	0.85	50.84
75	0.84	51.44
∞	0.83	51.95

The results of the analysis are given in the following figures:

1- The effect of truck velocity and location on the normal displacement of the bridge at mid-span (point 3) is given in figure 4 (radii of curvature 25m)

2- The effect of truck velocity and location on the transverse stress (Sx) of the bridge at mid-span (point 3) is given in figure 5 (radii of curvature 25m).

3- The effect of truck velocity and location on the longitudinal stress (Sy) of the bridge at mid-span (point 3) is given in figure 6 (radii of curvature 25m)

4- The effect of truck velocity and location on the shear stress of the bridge (Sxy) at mid-span (point 3) is given in figure 7 (radii of curvature 25m).

5- The effect of the type of the radial boundary conditions on the central displacement, transverse stress (Sx), longitudinal stress (Sy) and shear stress (Sxy) of the bridge (for a vehicle velocity of 60km/h) on the three radii of curvatures 25,50 and are given in figures 8,9,10 and 11 respectively.

6- The effect of the bridge slab thickness on the displacement and stresses are given in figure 12.

7- Comparisons of the maximum displacement along the center of span for all bridge radii are given in figure 13.
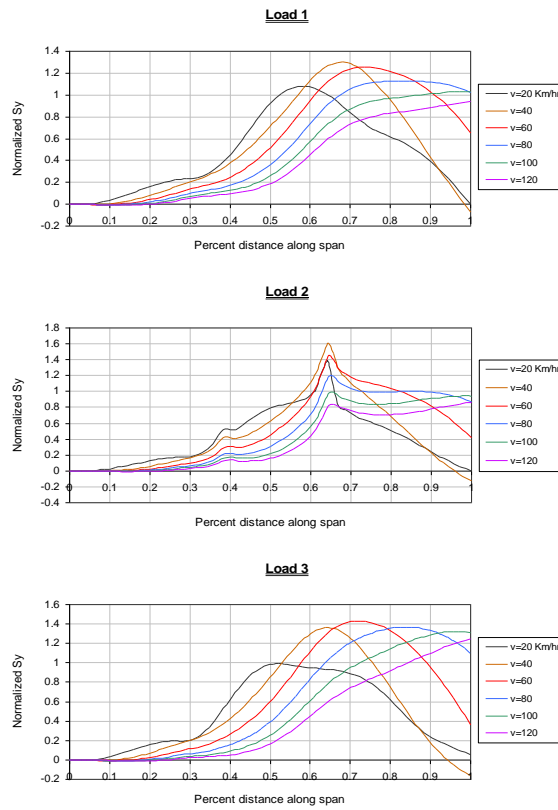
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Load 3
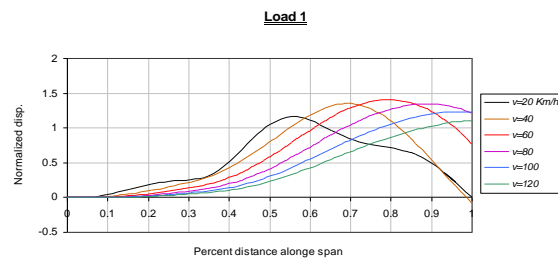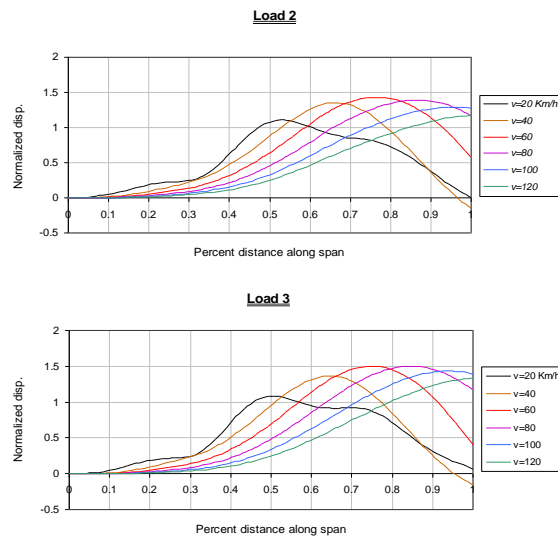
Figure 4: Effect of truck velocity on the displacement at point 3 (center of bridge) for a bridge thickness of 40cm and radii of curvature 25m. (a)- load on track 1. (b) load on track 2 and (c) load track 3.

Load 1

Load 2

Load 3
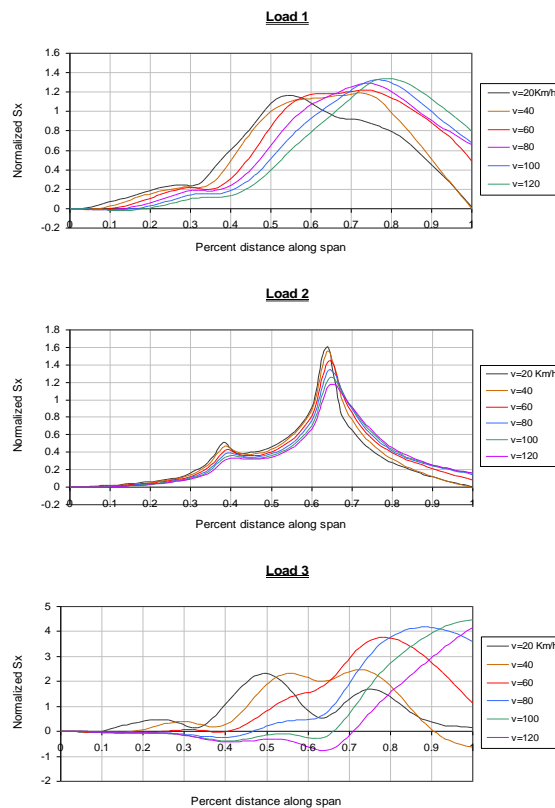
Figure 5: Effect of truck velocity on the transverse stress (Sx) at point 3 (center of bridge) for a bridge thickness of 40cm and radii of curvature 25m. (a)- load on track 1. (b) load on track 2 and (c) load track 3.

Load 1

Load 2

Load 3

Figure 6: Effect of truck velocity on the longitudinal stress (Sy) at point 3 (center of bridge) for a bridge thickness of 40cm and radii of curvature 25m. (a)- load on track 1. (b) load on track 2 and (c) load track 3.
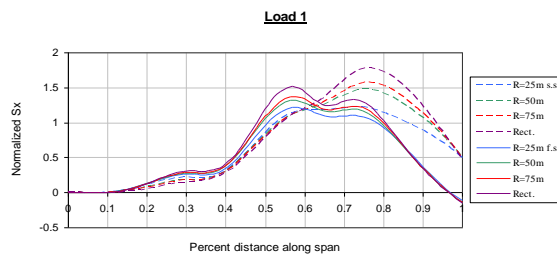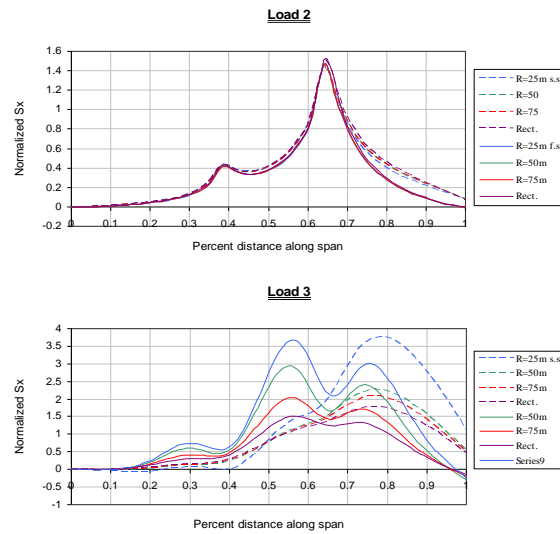
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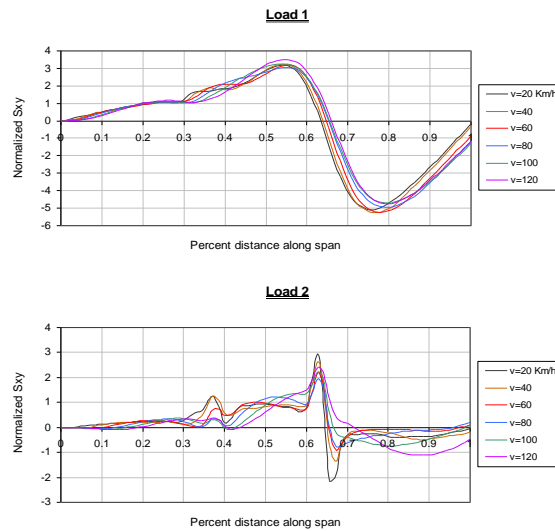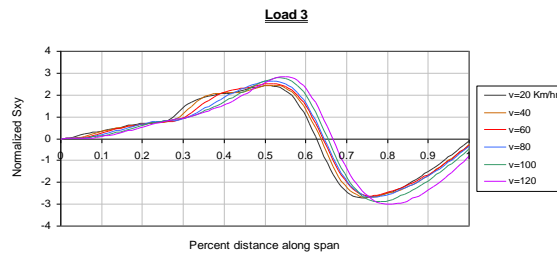
Figure 7: Shear stress (Sxy) at point 3 (center of bridge) for a thickness of 40cm bridge and a truck velocity 60km/h. for the two cases of boundary conditions. (a)- load on track 1. (b) load on track 2 and (c) load track 3.
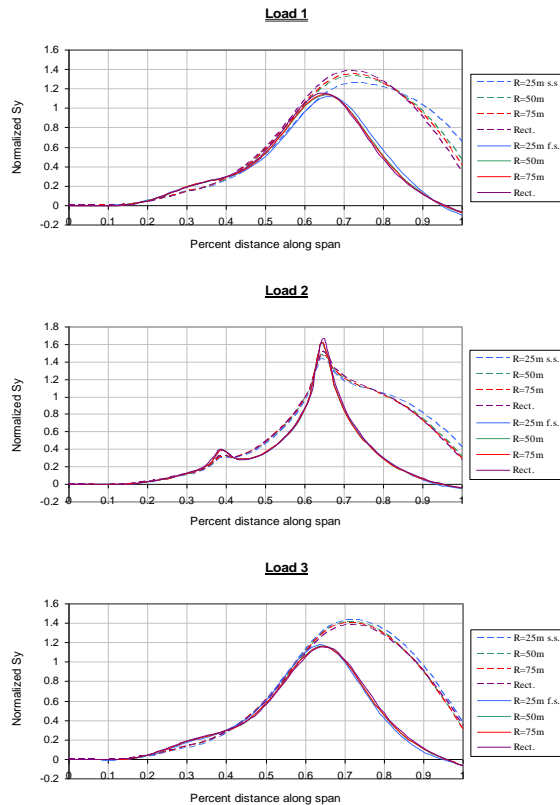
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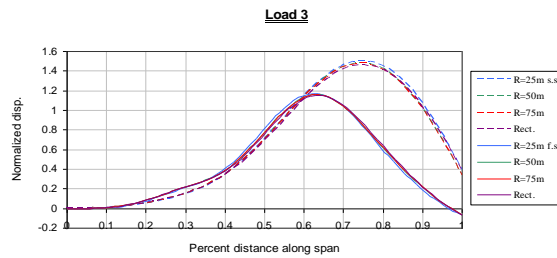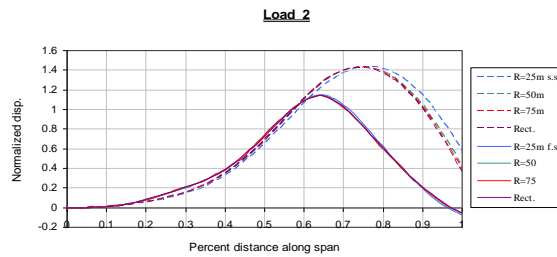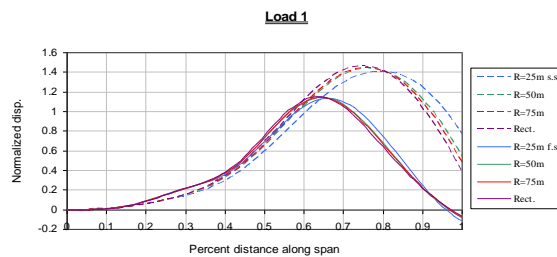
Figure 8: Displacement at point 3 (center of bridge) for thickness of bridge slab 40cm and truck velocity 60km/h. for the two cases of boundary conditions. (a)- load on track 1, (b)- load on track 2 and (c) load on track 3.
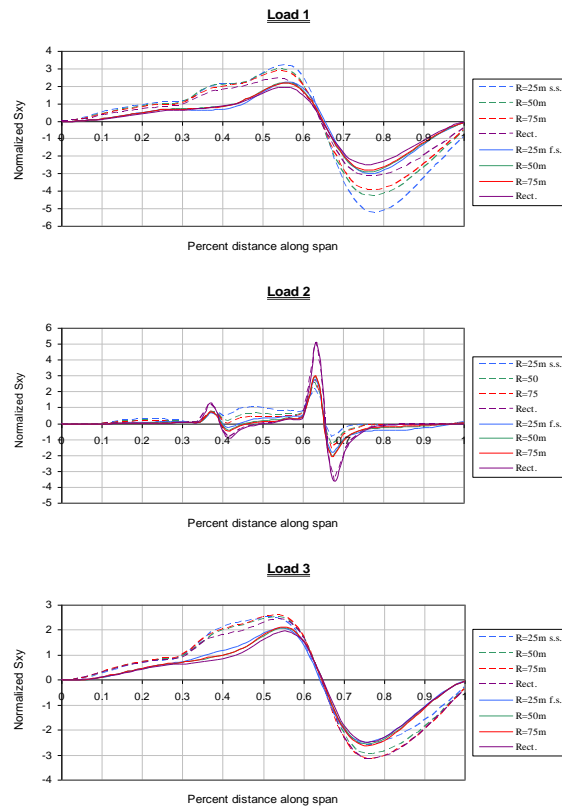
Load 1

Load 2

Load 3

Figure 9: Transverse stress (Sx) at point 3 (center of bridge) for a thickness of 40cm bridge and a truck velocity 60km/h. for the two cases of boundary conditions. (a)- load on track 1. (b) load on track 2 and (c) load track 3.

Load 1

Load 2

Load 3

Figure 10: Longitudinal stress (Sy) at point 3 (center of bridge) for a thickness of 40cm bridge and a truck velocity 60km/h. for the two cases of boundary conditions. (a)- load on track 1. (b) load on track 2 and (c) load track 3.

Figure 11: Shear stress (Sxy) at point 3 (center of bridge) for a thickness of 40cm bridge and a truck velocity 60km/h. for the two cases of boundary conditions. (a)- load on track 1. (b) load on track 2 and (c) load track 3.
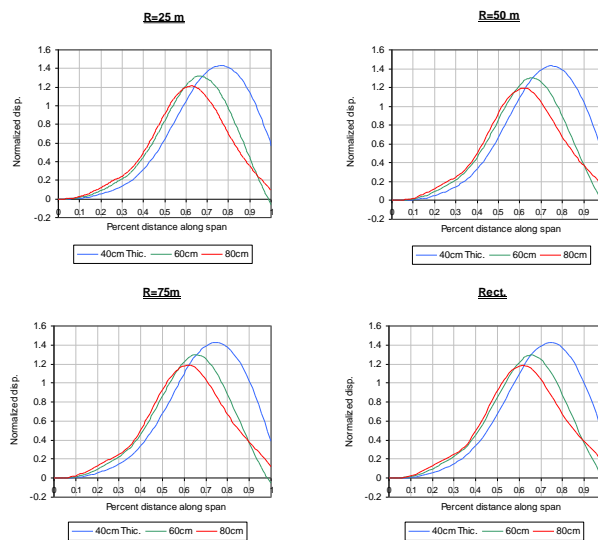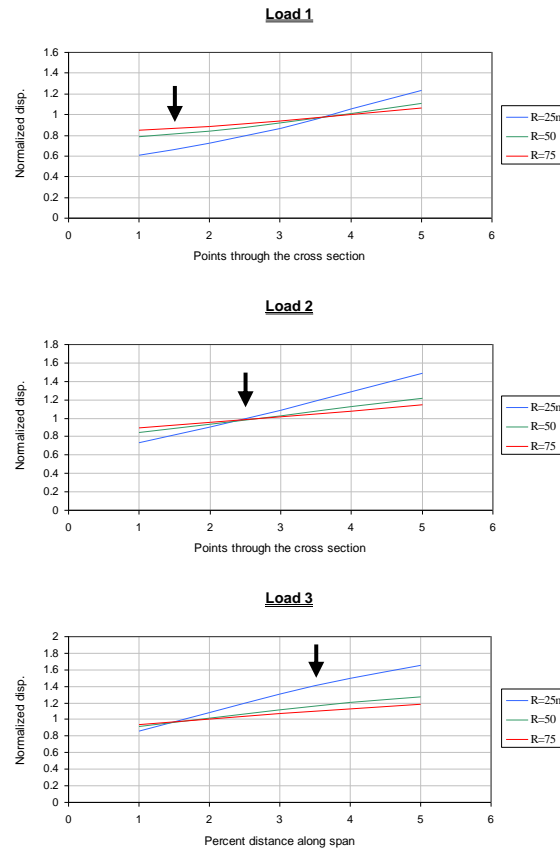

Figure 12: Effect of bridge thickness on the central displacement of the bridge for all radii of curvatures and load on track 2 (simply supported case).

Load 1

Load 2

Load 3

*Figure 13: Normalized displacements at the span center
of the bridge for all radii of curvatures (a) load on track
1, (b) load on track 2 and (c) load on track 3*

DISCUSSION

The results indicate that the velocity of the truck (load) has a clear magnification effect on the results (normalized displacements and stresses) at the center of the bridge span. This effect is ranging between 1.2 to 1.75 for the displacements, 1.35 to 4.5 for the transverse stress (Sx), 1.3 to 1.6 for the longitudinal stress (Sy) and between 3 to 5 for the shear stress (Sxy). The highest effects obtained when the truck speed (V) is ranging between (1.25 to 1.5 of V_f).

The position of the load application has a great influence on the results, Figures 4 and 5 shows that the maximum effect on the displacements and transverse stress (Sx) obtained when the load is applied on the outer track. Figure 6 shows that the maximum effect on the longitudinal stress (Sy) obtained when the load is applied on the middle track. While figure 7 shows that the maximum effect on the shear stress (Sxy) obtained when the load is applied on the inner track.

Figures 8 to 11 clarifies the effect of boundary conditions on the results (normalized displacements and stresses), as shown in the figures the results are greater for the case of simply supported bridge and the time for the maximum results are also greater in the case of simply supported bridge (as the fundamental period of the fixed supported bridge is less than that of the simply supported bridge).

Figure 12 clarifies the effect of the bridge slab thickness on the maximum resulted normalized displacements for all the radii of curvatures, it is clear that increasing the thickness reduces the normalized displacements and the time for the maximum effect which is mainly due to the reduction in the fundamental period of the bridge with the increase of the thickness.

The effect of radii of curvature of the bridge on the resulted normalized displacements is well clarified in figure 13. It is clear that increasing the curvature increases the variance in the normalized displacement across the width of the bridge and creates negative results on the inner side. The highest positive increase gained when the load moves near the outer edge while the highest negative increase gained when the load moves near the inner edge of the bridge with the highest curvature. The absolute variance between the inner normalized displacement and the outer one is 2, 1.4 and 1.3 for the bridges with radii of curvatures 25m, 50m and 75m respectively.

CONCLUSIONS

To study the influence of moving loads on the curved bridges, a finite element idealization of the problem is implemented and the ANSYS 5.4 soft-ware is used for the solution. Five different variables are considered and its effects are studied (the radius of curvature of the bridge, the velocity of the load and its movement location on the bridge, the boundary conditions along the radial directions of the bridge and the bridge thickness). The following conclusions can be drawn from the analysis results:-

1. The magnification of displacement at mid-span of bridge due to moving load and bridge curvature varies from 1.2 to 1.75. The maximum effect measured when the velocity of the load is about 1.25 to 1.5 from the velocity required by the load to cross the bridge in a time equal to the fundamental period of the bridge. For higher velocities of the load, the magnification of effects decreases as the load on the bridge is for a short time.
2. The magnification in transverse stresses (S_x) increases with increasing the curvature of the bridge and the maximum effect appeared when the load moves near the inner edge. The resulted magnification ranges from 1.3 to 4.5.
3. The resulted magnification due to moving load and curvature of the bridge is up to 1.6 and 5 in longitudinal stress (S_y) and shear stress (S_{xy}) respectively. And the maximum magnification in shear occurs when the load moves near the outer edge of the curved bridge.
4. The fixed support reduces the resulted effects as compared to the simple support by up to 25%.
5. Increasing the thickness/span ratio from 3.3% to 6.7% decreases the maximum effects (displacements and stresses) by 20%.
6. Some of the magnification values obtained exceeds that specified by AASHTO.

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