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# NUMERICAL STUDY OF DYNAMIC RESPONSE OF REINFORCED CONCRETE BRIDGE INDUCED BY SELECTED HEAVY VEHICLE

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### *Abstract*

*The main aim of this study is to carry out dynamic simulations of structural response of reinforced concrete bridge loaded with a moving heavy vehicle. Computational dynamics analysis was conducted using LS-DYNA computer code. The selected bridge was a reinforced-concrete structure located on the U.S. 90 in Northwest Florida. The bridge has six prestressed AASHTO type III beams and concrete deck. An 8-axle vehicle including a tractor unit and a low bed trailer were selected as a representative for the study. FE model of the tractor based on previous studies; however, a FE model of the trailer was developed for the present work. Analyses included passages of a vehicle with 47 tonnes cargo. A cargo resting on a trailer was taken into account by changing the material density of selected components in the semi-trailer FE model. Time histories of the bridge deflections in the middle of the span were recorded during the simulation tests. Simulations were performed for the vehicle velocity between 20 and 50 mph, stepped by 5 mph. An influence of the velocity on the bridge deflection was determined. The main objective of the simulation tests on the selected bridge was to assess the actual dynamic load allowance (DLA), also known as impact factor, based on the maximum deflection of the bridge span as a function of the vehicle velocity.*

***Keywords:*** *dynamic tests, bridges, vehicles, finite element method, LS-DYNA*

## 1. Introduction

A proper operation and maintenance of highway bridges can significantly reduce costs related with such infrastructure. Knowledge of the actual dynamic load effects and structure resistance is necessary to resolve the problem of deterioration of transportation infrastructure. Such information is useful for determining the load carrying capacity and the condition of the bridge structures. Moreover, it helps in making management decisions, such as establishing permissible weight and speed limits for certain roadways and bridges [8].

Formerly, bridges were often evaluated using simplified static analysis methods. Such approach did not represent actual responses of the structures, due to the negligence of dynamic effects. Therefore, the dynamic effects should be taken into consideration when evaluating existing bridges or designing new ones. An impact factor (now called dynamic load allowance, *DLA*) is frequently used to assess the dynamic effects of wheel loads on bridges. Previously, the magnitude of the impact factor was usually determined based on the simplifications and is related only to the length of the bridge [2], without reference to the bridge surface roughness and the dynamic characteristics of the vehicles. Recently, dynamic response of the bridges is quantified by the dynamic load allowance defined as follows [1]:

$$DLA = \frac{R_d - R_s}{R_s}, \tag{1}$$

where $R_d$ stands for a maximum dynamic response of any quantity (e.g. displacement or strain), whereas $R_s$ represents the static response of the same quantity.

Advanced numerical 3-D dynamic analyses of bridge structures can be carried out faster and easier than ever before due to an increase in computational capabilities of computers and the development of commercial finite element (FE) programs. FE models of bridges are more detailed; and contain a large amount of finite elements with consistent mass and stiffness distributions. Commercial FE software allow using advanced material models and options for modelling, which provides a more accurate description of the actual behaviour of the bridge [8].

Advanced FE models allow for analyses of complex mechanical phenomena such as contact between pavement and wheels, and dependence of moving live loads on time caused by dynamic interaction among suspended masses, which represent the vehicle and the bridge components. Validated FE models can provide extensive information about the structural behaviour, which is otherwise both expensive and difficult, if not impossible, to obtain solely through experimental studies [8].

The main aim of this study was to carry out dynamic simulations of structural response of reinforced concrete bridge loaded with a moving heavy vehicle. Simulations were performed for the vehicle velocity between 20 and 50 mph, stepped by 5 mph. The main objective of the simulation tests was to assess the actual dynamic load allowance based on the maximum deflection of the bridge span as a function of the vehicle velocity.

## 2. Finite element model of the bridge

The selected bridge is the three-span bridge #500133 (Fig. 1) with two lanes of traffic, built over Mosquito Creek in 1999 on U.S. 90 in Northern Florida. All three bridge spans are simply supported. Each span of the bridge consists of six AASHTO Type III prestressed girders. The bridge approach is characterized by a pavement depression, which may induced additional dynamic effects.

FE model of the bridge was developed within the framework of the research project titled *Analytical and experimental evaluation of existing Florida DOT bridges* [9]. The following five structural components of a single bridge span were developed as parts of its FE model: a slab, traffic railing barriers, AASHTO type III beams, diaphragms, and neoprene pads. The dimension of most finite elements and location of nodes in the bridge FE model were determined by the location of the reinforcement, requirements for contact between tyres and top surface of the deck, and a total number of elements.

The concrete components were modelled using 8- and 6-node solid, fully integrated elements with the elastic material model applied. Reinforcing bars used in the structure were modelled using 1D beam elements with the elastic material model applied. *MAT_CABLE_DISCRETE_BEAM material model was applied to introduce prestressing force in the rod elements using in the AASHTO III beams. This model allows elastic cables to carry tensile loads only, with no stiffness for compression. Three-dimensional solid element and *MAT_VISCOELASTIC material model were adopted to model the neoprene pads used to support each girder on bridge piers. The concrete bridge approach was modelled with three dimensional 8-node solid elements. Moreover, a short transient section of the asphalt pavement next to the beginning of the concrete approach was also modelled based on actual road profile obtained from the laser scanning.

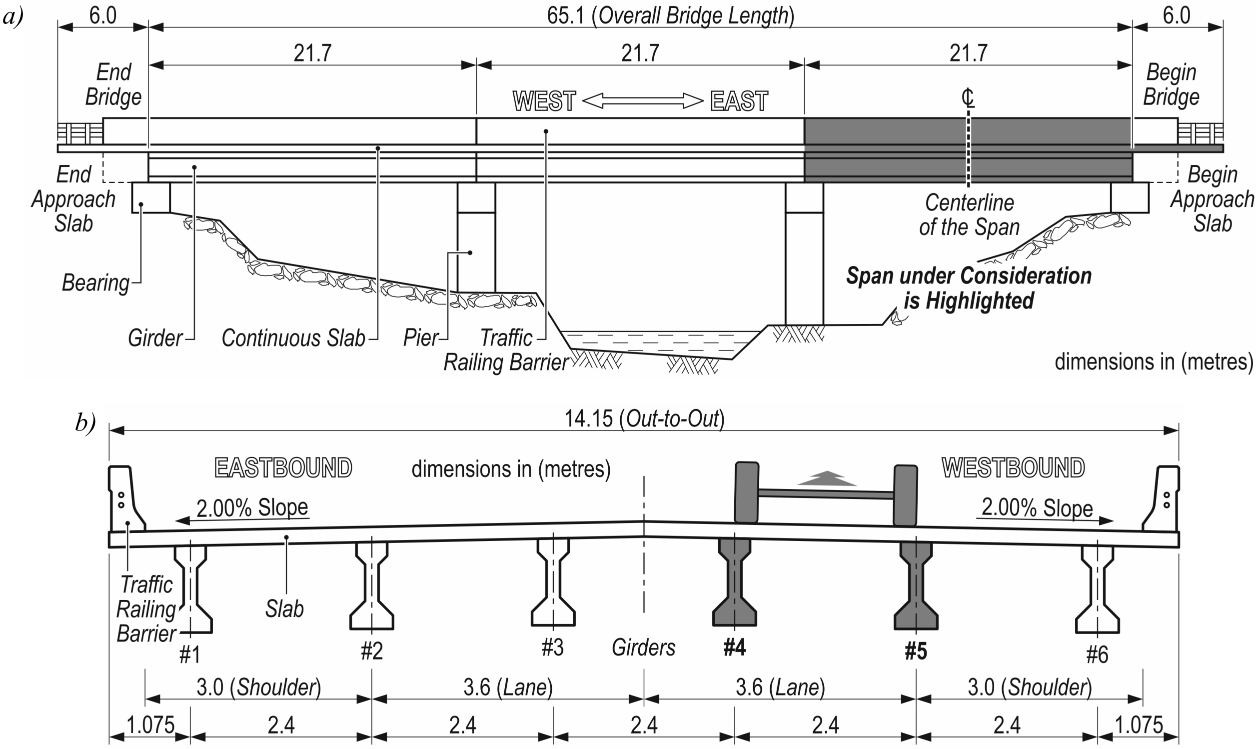

*Fig. 1. Bridge #500133 considered in the study: elevation of the bridge (a) and its cross-section (b) [9, 10]*

## 3. Finite element model of the vehicle

An 8-axle heavy vehicle including a tractor unit and a low bed trailer (Fig. 2) was selected as a representative for the study. A tractor unit under consideration based on popular 3-axle Mack CH613 truck. However, it was equipped with an additional rear axle to reduce axle loads. FE model of the tractor based on the model developed within the research project *Investigation of impact factors for permit vehicles* [10]. Modification was related only to the mentioned third axle and an extension of the frame. Detailed description of the base truck model can be found in [7, 10].

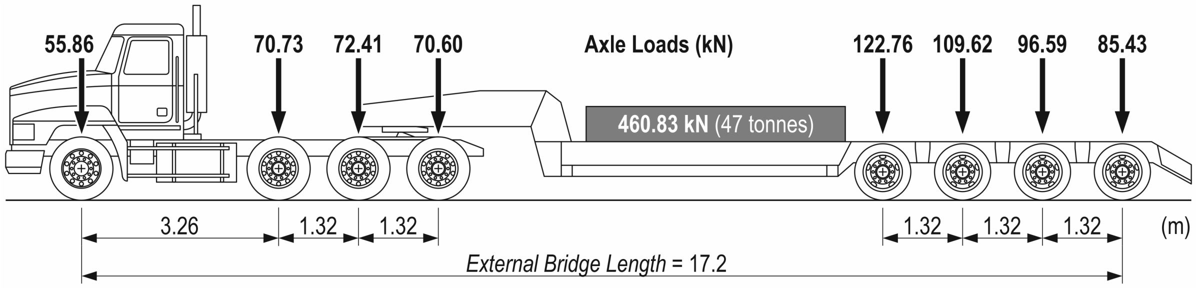

*Fig. 2. Configuration, axles spacing and the external bridge length of the heavy vehicle under consideration [4]*

A complete truck frame was modelled as an elastic part. Other components – including driver cab, hood, and engine – were modelled as rigid parts. The fifth wheel system was modelled for directly connect two units – the tractor and the trailer. A few details were added only to improve appearance of the FE model. They included a front bumper, fuel tanks and mudguards. Such modelling strategy resulted in simplifications in the FE model, as well as in reduction in the total number of elements and the CPU time.

Finite element model of the low bed trailer was developed in this study. CAD model was downloaded from the public database GrabCAD [3]. All structural components were simulated as deformable parts using 4-node shell element mostly. A cargo resting on a trailer was taken into account by changing the material density of selected components in the FE model. Suspension systems were strictly adopted from the trailer FE model developed within the framework of the previous project [10].

The suspension systems and the tyres received much attention in the modelling process as clearly having a distinct impact on the interaction between the vehicle and the road surface. Each suspension system includes several component modelled as rigid bodies using beam elements. Translational and rotational displacements between respective components were achieved by using the cylindrical and the revolute joints, and the special purpose discrete elements, which simulate springs and shock absorbers. Suspension characteristics were determined from the field tests conducted in earlier studies [6, 7, 10].

A FE model of each wheel consists of a rigid disc and a rim, and sidewalls and tread of the tyre. These two components includes two coincident layers of 4-node shell elements – the first layer represents a rubber-like material with average properties for rubber, whereas the second layer (representing the cord) uses a material model for fabrics, with stiffness for tension only. A simple pressure volume airbag model was used for the FE pneumatic models of the tyres.

Summing up, a FE model of the vehicle proposed in current study (Fig. 3) is hypothetical and it could not be verified. However, it significantly based on the earlier model which was already verified and validated. It can therefore be assumed that also this modified model is correct.

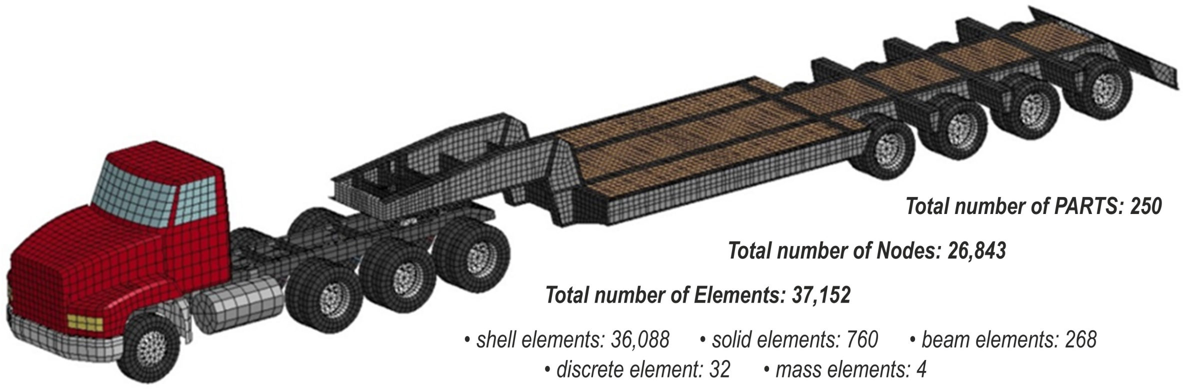

*Fig. 3. Complete FE model of the heavy vehicle under consideration [4]*

### 3.1. Selection of the heavy vehicle

Parameters of the heaviest vehicles permitted for crossing the bridge under consideration are provided in Tab. 1 [10]. These vehicles were multi-axle mostly and had a large external bridge length, defined as the distance between the centre of the first axle and the centre of the last axle of the vehicle (see Fig. 2). Data form Tab. 1 was taken into consideration during the selection of the vehicle for the current study.

*Tab. 1. Parameters of selected heavy vehicles permitted for crossing the bridge #500133 [10]*

| # | Gross vehicle weight (tonnes) \| (kN) | External bridge length (metres) | Equivalent distributed load (kN/m) | Number of axles | Average axle load (kN) |
|---|---|---|---|---|---|
| 1 | 90.27 \| 885.55 | 31.1 | 28.47 | 11 | 80.50 |
| 2 | 89.36 \| 876.62 | 29.3 | 29.92 | 10 | 87.66 |
| 3 | 77.11 \| 756.45 | 26.8 | 28.23 | 9 | 84.05 |
| 4 | 53.06 \| 520.53 | 16.6 | 31.36 | 6 | 86.76 |
| 5 | 69.72 \| 684.00 | 17.2 | 39.77 | 8 | 85.50 |
| Data in rows 1–3 based on information obtained from the FDOT Permit Office [10].<br>Data in row 4 based on measurement within the framework of the research project BD543 [10].<br>Data in row 5 relating to the vehicle under consideration in the present work [4]. | | | | | |

Two parameters were proposed in order to compare the actual loads caused by vehicles:

- *equivalent distributed load* (kN/m) – the ratio of the gross vehicle weight (kN) to the external bridge length,
- *average axle load* (kN) – the ratio of the gross vehicle weight (kN) to the number of axles.

An averaged value of the average axle loads from Tab. 1 is about 84.743 kN, therefore an 8-axle vehicle under consideration is supposed to have a weight of about 678 kN. A cargo equal to 47 tonnes was assumed, knowing the weight of the empty vehicle resulting from the weight of the modified tractor and the weight of trailer estimated based on its dimensions and density of steel. A cargo resting on a trailer was taken into account by changing the material density of selected components in the trailer FE model.

Static axle loads of the complete vehicle were determined based on the preliminary analysis in which the vehicle was dropped on planar rigid walls located under each axle. Finally, total load of the vehicle equal to 684 kN was adopted. Slight difference results from rounding off values and calculation error. Final results for the vehicle under consideration are provided in row 5 of Tab. 1.

External bridge length of the first three heavy vehicles summarised in Tab. 1 is higher than the span length of the bridge under consideration. Therefore, not all axles of the vehicle were located on the span while passing through the bridge. Vehicle selected in the current study is much shorter from those mentioned above are and all its axles can be situated on the span.

The average axle load obtained for the vehicle under consideration corresponds to the values given in Tab. 1 for other vehicles. However, the equivalent distributed load is much higher since the vehicle is quite heavy and quite short as well.

## 4. Simulation tests of dynamic response of bridge response

FE analyses of the interaction between a heavy vehicle and the bridge were performed using LS-DYNA computer code. Complete FE model of the whole system under consideration is depicted in Fig. 4. A transient section of the asphalt pavement, mentioned in chapter 2, is shown.

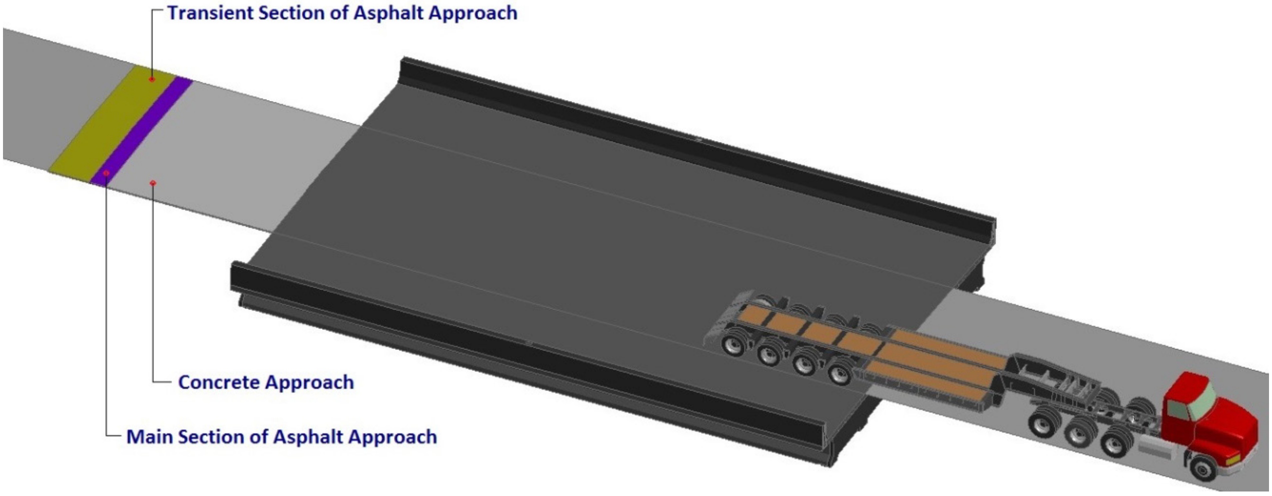

*Fig. 4. FE model of the whole system under consideration [4] – FE mesh not shown*

The vehicle FE model was moving on the westbound traffic lane (Fig. 1). Its wheels were located directly above the girders #4 and #5. Dynamic analysis required a motion of the vehicle FE model with a constant velocity. It was executed by a coupling of two commands available in LS-DYNA – *INITIAL_VELOCITY and *BOUNDARY_PRESCRIBED_MOTION. The first one was active only at the beginning of analysis. It was attributed both to all nodes of the FE model which had to move with a translational velocity and to all nodes of the wheels which had to rotate. In the next and following time steps, the motion of the vehicle FE model was achieved only by translational velocity applied to selected rigid components of the FE model. Wheels rotation was due to translational movement of their axles and the contact between wheels and the pavement.

Simulations were performed for the vehicle velocity between 20 and 50 mph, stepped by 5 mph. Time histories of the bridge deflections in the middle of the span were recorded during the simulation tests. Since the static analysis was not performed, a static response of the bridge was adopted from analysis at the lowest velocity of 20 mph.

Figure 5a presents time-history of the bridge deflection in the middle of the span for the fastest passage – velocity of 50 mph. Time 0 s corresponds to the location of the first axle of the vehicle at the beginning of the transient section of the asphalt approach (Fig. 4). Maximum deflections of each girder registered during this passage are shown in Fig. 5b. Naturally, extreme deflections appear for girders #4 and #5 located below the vehicle passing the bridge.

Bridge deflection for the girder #4 and #5 as a function of the vehicle velocity is depicted in Fig. 6. Deflection nonlinearly increases with an increasing of the velocity. Differences in deflection for the slowest and the fastest passage are about 0.18-0.19 mm.

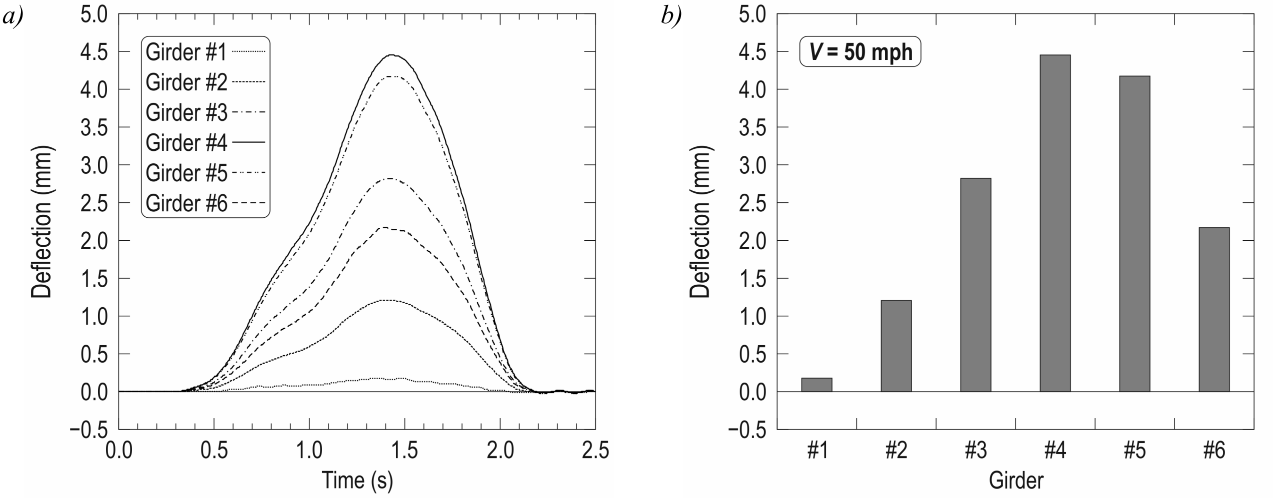

*Fig. 6. Time-history of the bridge deflection in the middle of the span (a) and maximum deflections of each girder (b)*

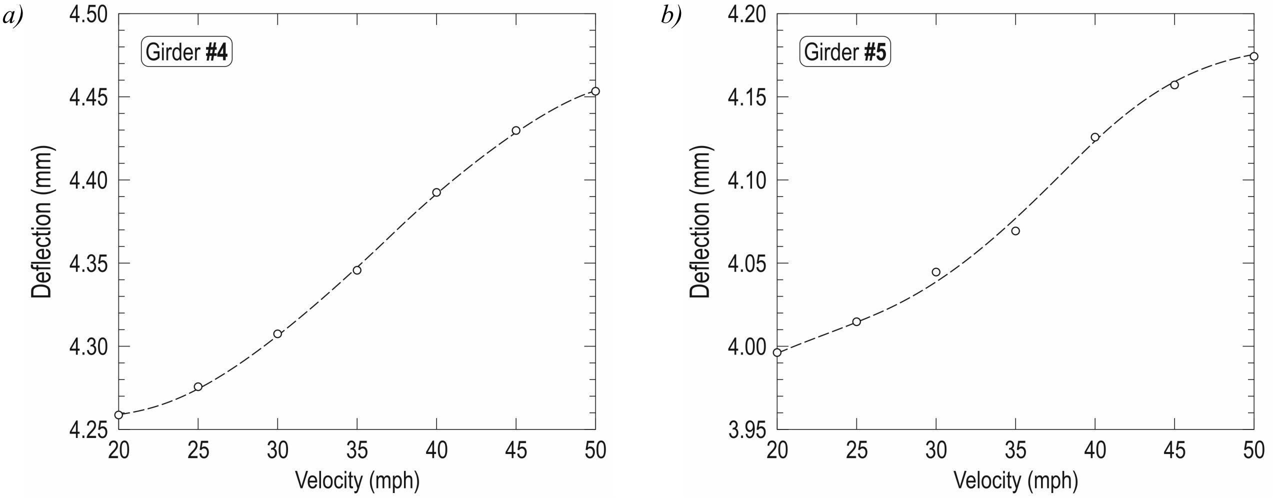

*Fig. 6. Deflection of the bridge in the middle of the span as a function of the vehicle velocity – girder #4 (a) and #5 (b)*

Dynamic load allowance (DLA) was calculated according to the formula (1) taking into account the above-mentioned comment regarding the static response. Results are limited only to the girders #4 and #5 since values of *DLA* obtained for other girders are slightly inappropriate due to relatively small deflections and differences between static and dynamic responses leading the large values of DLA. Moreover, the vehicle was located on the westbound traffic lane causing higher load on the right side of the bridge. Dynamic load allowance as a function of the vehicle velocity is presented in Fig. 7. Obtained values do not exceed 5%, which is significantly below 33% recommended by AASHTO LRFD [1].

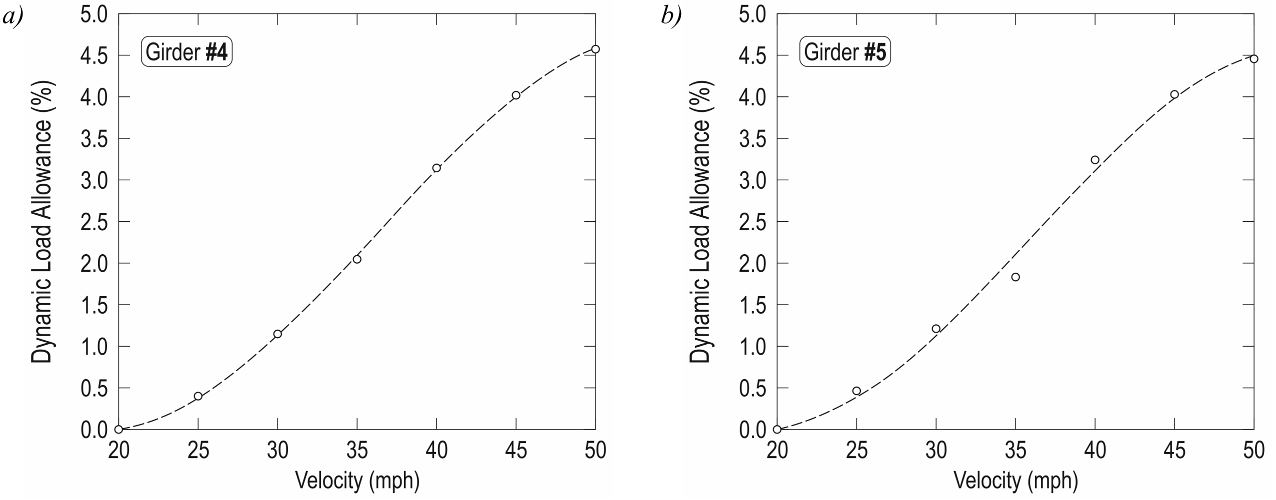

*Fig. 7. Dynamic load allowance as a function of the vehicle velocity – girder #4 (a) and #5 (b)*

## 5. Summary and conclusions

The paper presents results of simulation tests of the dynamic response of a reinforced concrete bridge induced by heavy vehicle. Proposed methodology, taking into account a 3D detailed model of the bridge, a 3D model of vehicle including rolling wheels with pneumatic tyres, and the pavement depression next to the beginning of the concrete approach, is correct. FE model of the vehicle proposed in current study is hypothetical but it based on the earlier model, which was already verified and validated.

Assessment of the actual dynamic load allowance (*DLA*) based on the maximum deflection of the bridge span was carried out. Obtained values of *DLA* are much lower from those recommended by AASHTO LRFD [1]. Therefore, the dynamic response of the vehicle-bridge system is limited, mostly due to full suspension of the vehicle. Moreover, multiple axles help for more evenly distribute the load and to control vibrations. It also has a positive effect on *DLA*. In addition, it is recommend calculating the dynamic load allowance for the most loaded girders only, since the obtained values of both static and dynamic responses are relatively high and differences between them allow for the most reliable determination of *DLA*.

Deflections rejected during the numerical simulation as well as the differences between static and dynamic responses were relatively small. Hence, *DLA* calculated based on the obtained data, is supposed to be considered in a qualitative respect instead of a quantitative one.

## Acknowledgement

*Finite element model of the bridge #500133 was developed within the framework of the research project No. BD493 Analytical and experimental evaluation of existing Florida DOT bridges. Finite element model of the tractor unit based on the vehicle model developed within the framework of the research project No. BD543 Investigation of impact factors for permit vehicles. Both projects were realized in the Crashworthiness and Impact Analysis Centre at the FAMU-FSU College of Engineering, under the supervision of Professor Jerry W. Wekezer, and supported by the Florida Department of Transportation. Authors are grateful for the opportunity to use both above-mentioned models in current studies.*

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