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DYNAMIC RESPONSE OF MODULAR STEEL BRIDGE FOLLOWED BY VEHICLE-BRIDGE INTERACTION

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Abstract. *This study aimed to investigate the effect of the interaction between vehicle and bridge on the dynamic response of modular steel bridges. The effect was examined by three-dimensional numerical analysis. This study covered one span simple steel bridge of 31m span length, which consists of combination of 12m + 7m + 12m standard girder modules using half-thick concrete-steel composite deck and bending steel girders. Three kinds of vehicle models - truck, bus, and car - were selected as analysis models. Dynamic response of the bridge while changing speeds of running vehicles was analyzed. In the case of bridge model, the following elements are used for idealizing its features: solid elements for concrete deck, shell elements for bottom steel plate and bending steel girders, rigid links and spring-dashpot systems for vehicle models. Known as Abaqus/explicit 6.12, the commercial finite element analysis program was utilized to simulate the vehicle-bridge interaction for this analysis. In accordance with the running vehicles' features and speeds, the changing aspects of the impact factors and time history of dynamic behaviors were calculated by numerical analysis. This was compared with the bridge design code.*

1 INTRODUCTION

It is necessary to examine the aspect of dynamic behavior as well as static behavior in order to employing the modular bride, current temporal bridge with narrow permission, as a permanent bridge. For this reason, the dynamic behavior of modular steel bridges is analyzed by using interactions between vehicles and bridges with considering the impacts of vehicle loads to the dynamic response of bridges in this paper.

The dynamic response arose from highway bridge is influenced by dynamic features of vehicle and bridges, road surfaces and so on. Since it is difficult to precisely comprehend the dynamic response affected by various factors, current LRFD specification indicates DLA in reasonably refined simple way based on interpretation and experiment result for the sake of regarding the dynamic effect of vehicles while allowable stress design specification defines impact factor. Researches pertaining to DLA are aggressively conducted in Canada in which a plenty of data have been cultivated from 1950 up to nowadays. These materials are foundation stone of Canada Specifications and OHBDC.

In this paper, the steel bridge in total 31 m length combined 12 m + 7 m + 12 m girder module and synthetic deck plate module is adopted as the subject bridge with exploiting standard module invented by Research Institute of Industrial Science & Technology(RIST). Vehicles confine to truck, bus, car. Depends on passing types of vehicles and passing speed levels, impacted coefficient and DLA are figured out and the effects are comparably analyzed.

2 EQUATION OF MOTION FOR VEHICLE AND BRIDGE

Bridges are affected by the various factors such as loads of vehicles, lengths, suspension system and natural periodicity. It is practically difficult task to model with the consideration of all variables as these factors indirectly interact in complex way. For this reason, several assumptions are set in this paper and indicated below.

- Vehicles confine to three types of trucks, buses and cars.
- Vehicles are passing through with steady speed and made of rigid bodies.
- When vehicles drive, there is no frictional force between tires and road surfaces.
- Vehicle models are employed with stiffness and damping for consideration of interaction between bridge and vehicles.

2.1 Vehicle Models

Tri-axial truck model is consist of two rigid bodies such as car body (m_1), and trailer (m_2) and also the degree of freedom (DOF) of each wheel is also composed of vertical displacement (z'_1, z'_2), pitching rotation (θ_1, θ_2), and rolling rotation (α_1, α_2). In addition, as shown in Figure 1, spring-dashpot systems are also attached to each mass in order to simulate a real truck. Based on the principle of virtual work, equilibrium equation of motion for vehicle having 11degrees of freedom is constituted by the relationship from the gravity (M_{1g}, M_{2g}, m_{ig}, $i = 1 \cdots 6$), inertia force and moment ($M_j \ddot{Z}_j$, $I_{\theta j}\ddot{\theta}$, $I_{\alpha j}$, $\ddot{\alpha}_j$, $j = 1,2$; $m_i \ddot{z}_i$, $i = 1 \cdots 6$), suspension force (F'_i, $i = 1 \cdots 6$), to tire force (F_i, $i = 1 \cdots 6$) (Zeng and Bert 2003). The numerical analysis model considered in this study is depicted in Figure 1.

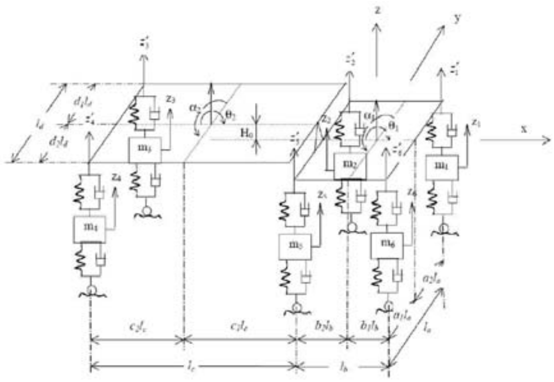

Figure 1: Tri-axial truck model.
(Zeng and Bert, 2003)

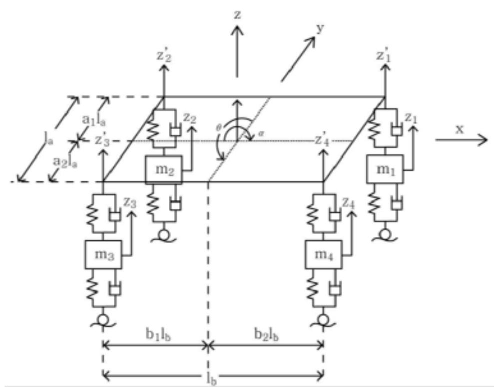

Figure 2: Bi-axial bus and car model.
(Zuo and Nayfeh, 2003)

The model can be expressed in simple matrix structure with mass matrix of a vehicle M_v, damping matrix C_v, stiffness matrix K_v, reaction vector F_{bv} and gravity vector G_v as Eq. (1)

$$M_v\ddot{Z}_v + C_v\dot{Z}_v + K_vZ_v = F_{bv} + G_v \tag{1}$$

Vehicle	Truck	Bus	Car
Mass	$m_1 = m_6 = 0.250$, $m_2 = m_3 = m_4 = m_5 = 1$, $M_1 = 3.323$, $M_2 = 27.821$	$m_1 = m_4 = 0.34$, $m_2 = m_3 = 0.55$, $M_1 = 10.724$	$m_1 = m_4 = 0.04$, $m_2 = m_3 = 0.04$, $M_1 = 1.376$
Inertia Moment	$I_{\theta 1} = 1.4055\times10^7$, $I_{\theta 2} = 2.4934\times10^7$, $I_{a1} = 1.108\times10^6$, $I_{a2} = 9.274\times10^6$	$I_{\theta 1} = 2.807\times10^7$, $I_{a1} = 4.211\times10^6$	$I_{\theta 1} = 2.344\times10^6$, $I_{a1} = 4.84\times10^6$
Stiffness of Tires	$k_{t1} = k_{t2} = 2250$, $k_{t2} = k_{t3} = k_{t4} = k_{t5} = 8000$	$k_{t1} = k_{t2} = 1027$, $k_{t3} = k_{t4} = 2054$	$k_{t1} = k_{t2} = k_{t3} = k_{t4}$ $= 182.087$
Stiffness of Bodies	$k_{s1} = k_{s2} = k_{s3} = k_{s4}$ $= k_{s5} = k_{s6} = 4000$	$k_{s1} = k_{s4} = 230$, $k_{s2} = k_{s3} = 2123$	$k_{s1} = k_{s4} = 20.985$, $k_{s2} = k_{s3} = 19.122$
Damping coefficients of Tires	$c_{t1} = c_{t2} = c_{t3} = c_{t4}$ $= c_{t5} = c_{t6} = 20$	$c_{t1} = c_{t4} = 3.5$, $c_{t2} = c_{t3} = 7.0$	$c_{t1} = c_{t4} = 1.306$, $c_{t2} = c_{t3} = 1.470$
Damping coefficients of Bodies	$c_{s1} = c_{s2} = c_{s3} = c_{s4}$ $= c_{s5} = c_{s6} = 20$	$c_{s1} = c_{s4} = 10.74$, $c_{s2} = c_{s3} = 3.0$	$c_{s1} = c_{s4} = 1.306$, $c_{s2} = c_{s3} = 1.470$
Coefficient of Vehicle Dimensions	$l_a = 1830$, $l_b = 2636$	$l_a = 1830$, $l_b = 5400$	$l_a = 1440$, $l_b = 2636$
Coefficients of Center of Mass	$a_1 = 0.5$, $b_1 = 0.3$, $c_1 = 0.5$, $d_1 = 0.5$	$a_1 = 0.5$, $b_1 = 0.66$	$a_1 = 0.5$, $b_1 = 0.43$

Table 1: Properties of Vehicles.

The Eq. (1) is equation of motion which can apply dynamic behavior using mass, damping and stiffness of vehicle. This research modelled a truck having 11 degree of freedom using the Eq. (1).

Each of six tires is generated with three nodes to consider spring coefficient and damping coefficient. Four front tires are connected with one node for load of frontal car and two rear tires are connected with another node for back part of a car. Moreover, these two nodes are attached to each other making another node to apply the load of the whole car. Unless truck model, models for car and bus are also generated to be applied into real moving vehicle load scenario. Even though there are various kinds of vehicles in real transportation situation, models for truck, car and bus are employed to represent them. The truck model can be modified with the equations above to generate car and bus model. The trailer with mass m_2 is removed from the three axles of truck model on Figure 1 and the main body with mass m_1 is transformed into car and bus model.

Figure 2 shows the car and bus model with six degrees of freedom as four front tires are connected to one node to apply the load of whole vehicles. Equation of motion of the car and the bus can be also expressed as Eq. (1). Data employed to each vehicle are given in Table 1.

2.2 Bridge Model

In this study, covered bridge is modular bridge utilizing steel girder module with U-type bending section developed in RIST. This bridge is composed with two girders that each girder can be loaded a traffic lane. This research is on the subject of a bridge having span length of 12 m + 7 m + 12 m by combining two 12 m standard modules and a 7 m standard module. The deck module is combination of steel plate and concrete so that the thickness of concrete deck becomes half of its original. Moreover, we assume the good state by using roughness coefficient suggested by Dodds and Roboson(1973). International Organization for Standardization (ISO) has assorted the road surface roughness into four levels: Very Good, Good, Average, and Poor. The roughness coefficient generation method is under assumption of normal distribution with zero mean and uses function of power spectral density (PSD) and it is applied to this study.

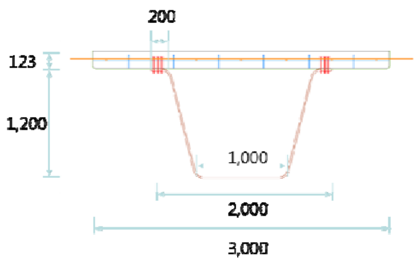

Figure 3: Cross section of bridge..

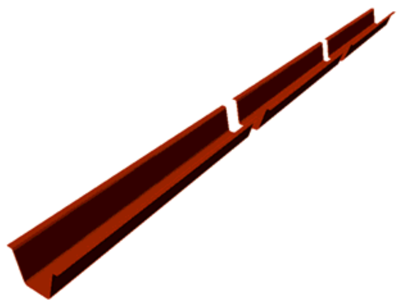

Figure 4: Combination of girder modules.

3 THREE DIMENSIONAL NUMERICAL ANALYSIS

In order to figure out the vertical displacement of center span, Basic assumptions are considered in this study. These are as follows:

- In this study, self-weights of bridge and vehicles are considered to apply live load. Inertia force and suspension systems of vehicles are also considered using moving vehicle load.
- Slab of three dimensional bridge model is created as concrete and it has unit weight of 2,300 kgf/m^3 and elastic modulus of 30 GPa.
- Girders of three dimensional bridge model are created as steel and it has unit weight of 8,000 kgf/m^3 and elastic modulus of 200 GPa.
- Bridge model is simply supported beam.
- Thickness of deck is fixed in size as 120 mm of concrete and 3mm of steel plate.
- All of materials are in elastic limit and assumed as homogeneous and isotropic.

Proper elements for each modules are selected and created respectively, for three dimensional finite element analysis of above bridge model. Numerical analysis is performed by using commercial finite element analysis program ABAQUS 6.12. Concrete deck of bridge is modeled as three dimensional solid element(Linear Hexahedral Element, C3D83) and bottom steel plate is modeled as three dimensional shell element(Linear Quadrilateral Element, S4R). Using tie-constraint, concrete deck and steel plate are able to behave identically and this respect is considered in analysis. Girder is used three dimensional shell element essentially. Approaching slabs are applied at both of start and end parts of bridge model so that running vehicles can pass through the bridge naturally.

Above all, flexural and torsional mode shapes are checked, which affect to the vertical vibration of bridge while vehicle go through the bridge. Modular bridge with two girders is considered and natural frequencies are verified. It is verified that natural frequency of first flexural mode is 3.237 Hz and second natural frequency of flexural mode is 11.313 Hz. First torsional mode is indicated as natural frequency of 12.467 Hz.

During dynamic analysis, the velocities of running vehicle are considered every 20 km/h from 60 km/h to 140 km/h. Dynamic behavior of bridge is analyzed while vehicle passes through the bridge completely from before entrance. Three types of vehicles; truck, bus, and car, which are referred to in previous chapter, are analyzed and compared. In the case of truck, it takes about 2.4 seconds for 60 km/h and about a second for 140 km/h that front axle of truck enters to and rear axle of truck exits from the bridge. The relationship between speed of running vehicle and vertical displacement of bridge does not exactly correspond to similar tendency. In general, however, the faster vehicle is, the bigger the maximum amplitude of vibration is. These results are shown as Figure 5~7 and Table 2. The first vibration amplitude, which is aroused from vehicle entry to bridge, is proportional to the square of the vehicle speed exactly. This is just the results reflected the inertia force of vehicles. Since then, however, the amplitude is the result from vehicle-bridge interaction and to know these effects, an additional in-depth study is requested. In case of bus and car, the results are similar with the result of truck.

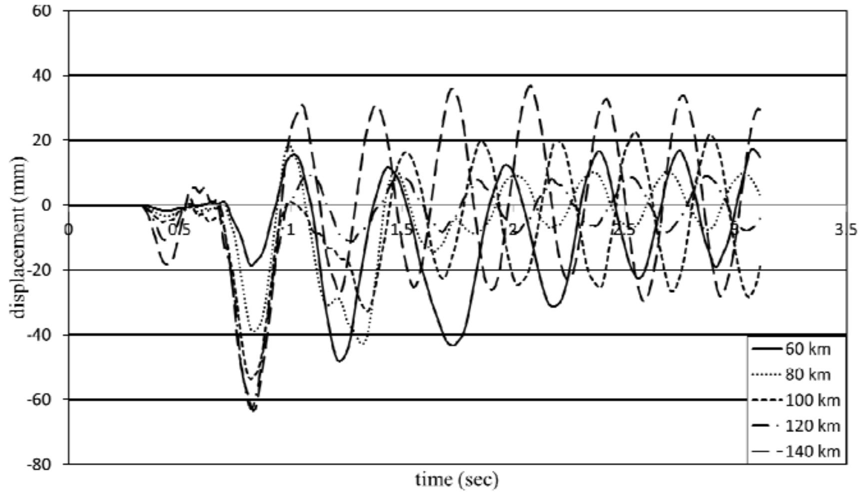

Figure 5: Displacement time history - truck.

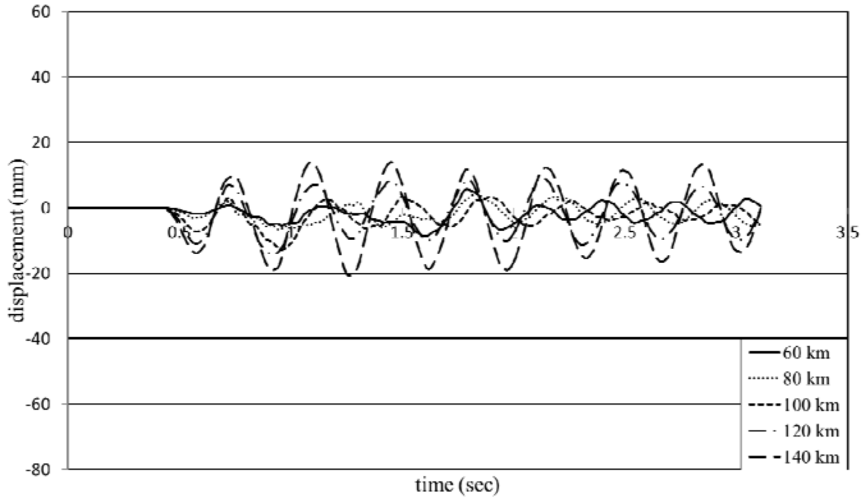

Figure 6: Displacement time history - bus.

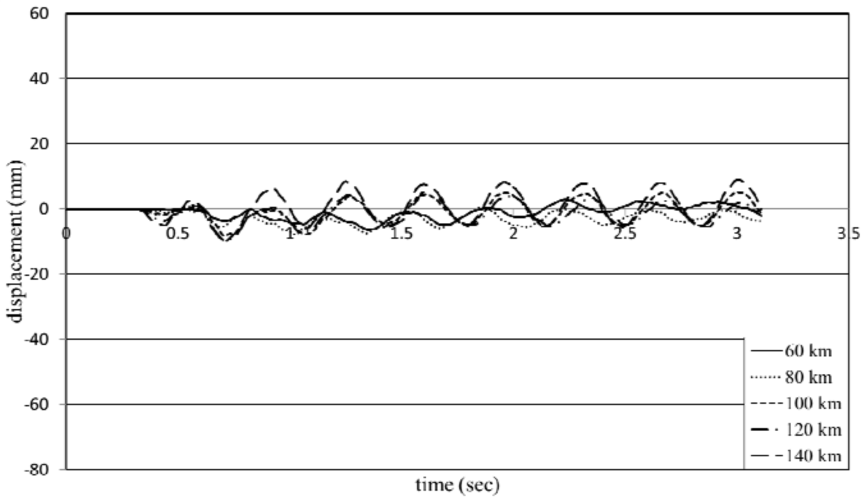

Figure 7: Displacement time history - car.

Velocity (km/h)	Truck			Bus			Car		
	Amp.1 (mm)	Amp.2 (mm)	Disp. (mm)	Amp.1 (mm)	Amp.2 (mm)	Disp. (mm)	Amp.1 (mm)	Amp.2 (mm)	Disp. (mm)
60	62.27	33.80	48.18	13.83	7.13	8.11	5.29	2.12	6.47
80	57.43	16.73	42.01	7.77	7.37	7.05	6.86	3.12	8.12
100	53.24	48.86	51.79	15.69	5.95	12.43	11.49	9.91	8.65
120	71.91	15.26	62.11	15.08	16.50	14.12	11.28	6.93	10.49
140	92.10	61.17	63.24	33.11	27.19	20.89	16.34	13.79	9.98

Table 2: Results of time history analysis

In Table 2, Amp.1 and Amp.2 mean the maximum amplitude of vehicle traffic and of residual vibration, respectively. Disp. means the maximum displacement of bridge at center span. Using Eq. (2), impact factor of bridge is calculated about displacement of center span.

$$I = \frac{D_{dyn} - D_{sta}}{D_{sta}} \tag{2}$$

Here, I is impact factor, D_{dyn} is the maximum dynamic displacement, and D_{sta} is the maximum static displacement. Loading the truck model, the impact factor is distributed in a range of 0.05~0.47. This result is over than the value, $I = 15/(40 + L)$, proposed by Korean Bridge Design Specification Interim. Comparing the relative mass among the separate vehicles, it is verified that the vehicle with relatively less mass has relatively greater impact factor.

4 CONCLUSIONS

Throughout this study, using three dimensional dynamic analysis considering vehicle-bridge interaction, several developments and key results were determined as follows:

- The relationship between speed of running vehicle and vertical displacement of bridge does not exactly correspond to similar tendency. In general, however, the faster vehicle is, the bigger the maximum amplitude of vibration is.
- Generally, the maximum amplitude of vehicle traffic is proportional to the speed of vehicles, but amplitude of residual vibration has weak tendency relative to the speed of vehicles.
- Developed modular bridge is designed based on Korean Bridge Design Specification Interim, so that its use is expected to expand as permanent bridge if dynamic behavior is complemented.

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