

SIMULATION OF MOVING PARTS ON FLEXIBLE BODIES USING MULTIBODY APPROACH. TEST CASE ON A REINFORCED CONCRETE HIGHWAY BRIDGE

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ABSTRACT

In this paper a new MBS tool, allowing the simulation of moving parts on flexible bodies, is shown, implemented by the authors in ADAMS environment and comprising a customized GUI for A/View.

A test case considering traffic testing on a reinforced concrete highway bridge is illustrated. Dynamic traffic tests and relative MBS simulations are reported and compared in terms of acceleration. Moreover, using a new Stress Recovery procedure implemented by the authors for a particular MBS/FEM (ADAMS/ANSYS) environment, a comparison was realized between stress test measurements and numerical ones.

INTRODUCTION

The use of flexible bodies in mechanical systems dynamic simulation has become very important during the last years; a lot of application has been developed featuring the presence of flexible bodies within multibody systems.

An important item about flexible bodies is represented by the interaction between moving equipment and FB dynamics.

In fact it is well known that the presence of bodies moving along a flexible structure modifies the dynamics of the system (eigenvectors) because of the coupling of the masses.

This phenomenon may be very important to be predicted, especially when dealing with big structures (for example bridges crossed by vehicles).

This paper has the aim to show a particular application of a tool developed to give the capability to have parts moving on flexible bodies in ADAMS.

THE TOOL

Flexible bodies within the standard ADAMS environment may be introduced in several ways; the most popular and powerful is ADAMS/Flex, which gives the capability to import meshes from FE, according to the theoretical background from Craig and Bampton (component mode synthesis). Using this approach it is possible to describe the flexible body dynamics referring to a modal superposition. The mode shapes which are considered within ADAMS derive from an orthonormalization of normal and static correction modes.

In force of this formulation it is supposed that the connection between the flexible body and the rest of the system happens at the "interface nodes". Respecting this hypothesis we are sure that we can have a good description of static deformation of the system without having to consider a huge number of normal modes.

Related to this fact we notice that multi-component forces can be applied in ADAMS directly to a flexible body only if the flexible part is the l-part of the force itself. In fact ADAMS use a

floating marker to identify the J-part application point, but does not allow to have floating markers on a flexible body.

The idea at the base of this application is to enhance the standard ADAMS capabilities, creating a new user defined ADAMS element which will allow a part to move along a flexible body.

Depending on what we've already shown (we can't have moving entities on a flexible body in standard ADAMS), the concept may be seen split in two parts:

- 1) the implementation of the forces acting on the flexible body;
- 2) the definition of the motion of the "moving" part along the deformed shape of flexible body. This could be implemented using a special point to curve constraint.

Referring to the second item, ADAMS features the capability to create a particular joint between a point and a curve; this constraint removes two DOFs to the overall system; the curve on which the point is moving has to be specified using a CURVE statement, which gives the information about the curve coordinates and derivatives; usually the curve is defined by a sequence of points belonging to a single part (i.e. from geometric features in the model) therefore being un-deformable during the whole analysis (once defined, the relative position of curve points will not change).

Obviously this is not acceptable for this application because we would need a curve belonging to flexible part and this means that the relative position of curve points could change during simulation.

To implement this idea the curve reference has been created on the ground part, and a special user sub-routine has been written. The curve is defined using a cubic spline 3D interpolation of the points laying on the flexible body; doing so it is "flexible" and may be used anyway for a point to curve constraint.

Some further elements are needed to complete the flexible point to curve contact element.

A sketch of the connectivity topology of the "flex_PTCV" user defined element is shown in figure 1.

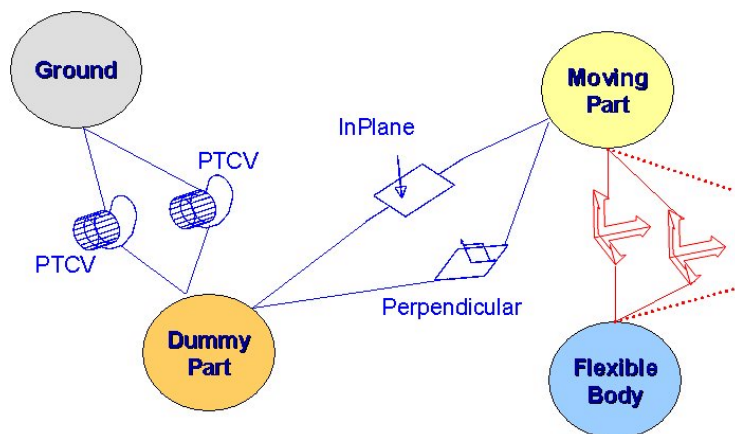


Fig.1 - Connectivity topology of Flex PTCV element

The part which is effectively moving along the curve is a "dummy" part which is connected to the curve by two standard point to curve constraints; so that it has two DOFs free w.r.t. the curve part itself: the translation along the instantaneous curve tangent direction and the rotation around the same direction. The i-node of each PTCV connection is referencing the dynamic curve.

The real moving part is constrained to the dummy part by two primitive joints (a perpendicular and an InPlane one).

This combination of constraints make the moving part able to translate the along the instantaneous curve tangent direction, being the rotation around the curve tangent direction and the translation itself, the same of dummy part (free). The moving part is still kinematically free to move in curve normal direction.

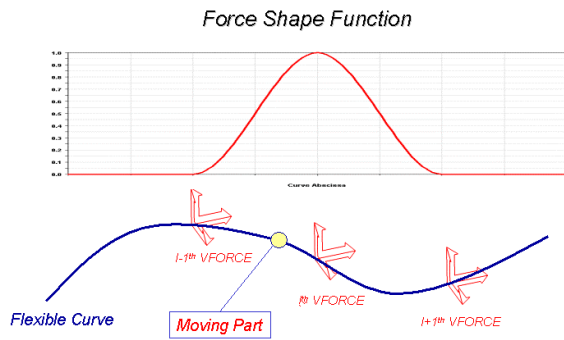


Fig.2 - Force Shape Function

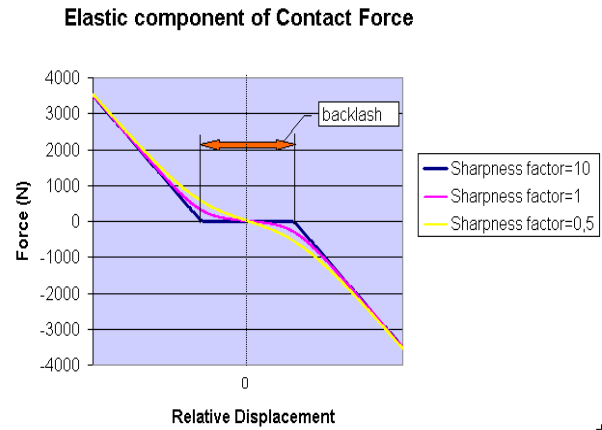


Fig.3 - Elastic component of contact force

To limit these DOFs, contact forces (VFORCES) between the Flexible part and the moving one are used. A set of vector forces is being created acting on the Flexible body (j-marker on moving part), to correctly distribute the reaction forces of each PTCV connection along the curve path.

The expression of vector forces uses a sort of “spring – damper” definition, using the relative displacements and velocity between moving part and dummy part as independent variables. This fact allows to transfer the PTCV contact reactions from moving part to flexible body correctly.

The resultant contact forces are distributed between the different Flexible Body Vector forces, using special shape functions, depending on moving part position along flexible curve as shown in figure 2.

According to the previous figure the reaction contact forces are spread between the reaction points previous and following the moving part.

This is to assure that the deformation of the flexible curve are congruent with the

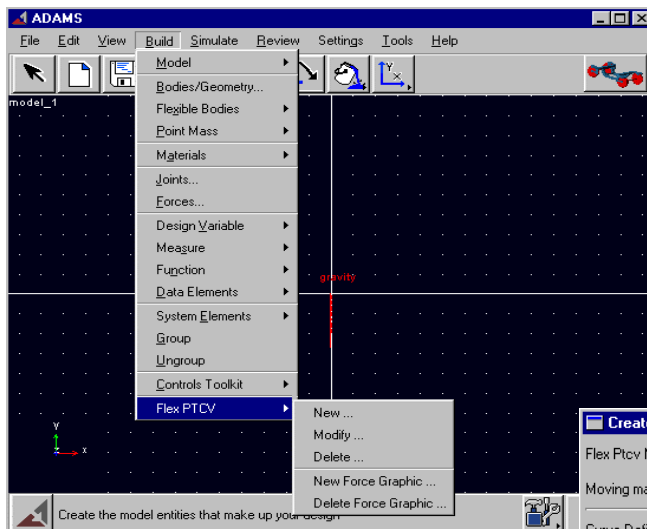


Fig.4 - Flex PTCV User Interface

loads resulting from the point to curve constraint.

Furthermore in some applications it could be useful to comprise the effect of backlash in the motion of the moving part along flexible body.

To accomplish this, a special function expression has been introduced in Vector Forces, so that the reaction is zero while

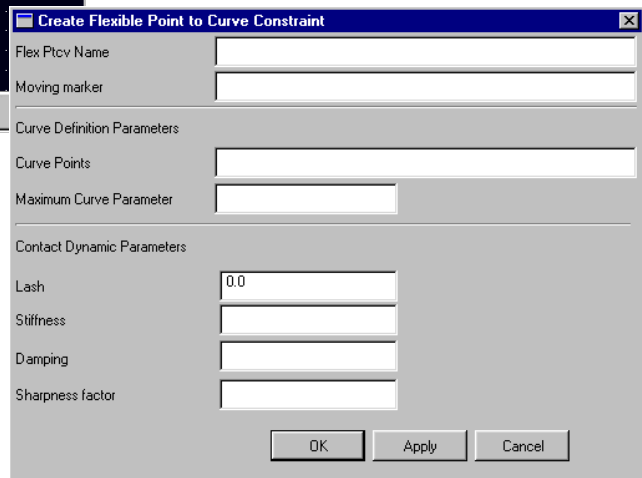


Fig.5 - Flex PTCV Dialog Box example

relative displacement is within a specified backlash.

The transition between the lash and contact is managed by a sharpness factor parameter keeping the function continue.

Figure 3 shows an example of the relation elastic component of contact force and some of its parameters (backlash, sharpness factor).

A user interface has been created within A/View to allow a few picks creation of models with flex PTCV contacts (see figure 4 and 5).

The user will find dialog boxes to create, modify and delete the new user defined elements and some extra tools to generate force graphics for reaction forces on flexible body visualization during animations.

Depending on the fact that ADAMS Solver computes the dependency of the system on the curve definition (expecting that it is rigid), basically at the beginning of simulations, some convergence troubles may be encountered during analysis ; anyway the use of the new GSTIFF corrector or Stabilized Index 2 integrator together with a "ALL TRUE" Jacobian evaluation pattern, have shown a good robustness of the tool figuring its integration in different ADAMS packages (A/rail, A/Car etc.).

TEST CASE

A test case considering traffic testing on a reinforced concrete highway bridge is illustrated. Experimental tests were realised within a research program developed by Department of Industrial Engineering of Perugia University in co-operation with the Administrative Department of Perugia. The aim of the co-operation was to analyse and evaluate the structural performance of the bridges of the Perugia highway system. Extended results of this activity are illustrated in reference [1].

General description of the bridge

The tested structure was a 55 m two-lane reinforced-concrete highway bridge. Figure 6 shows the basic dimensions of the structure. This bridge, over the Chiascio river, is called "the Costano Bridge" because it is located near the village of Costano, 15 Km away from Perugia along the road which links Costano to Torgiano.

The effective construction date is not know. Nevertheless, considering the typology and the material of the bridge itself, it was presumably built in the 1950-1960 decade.

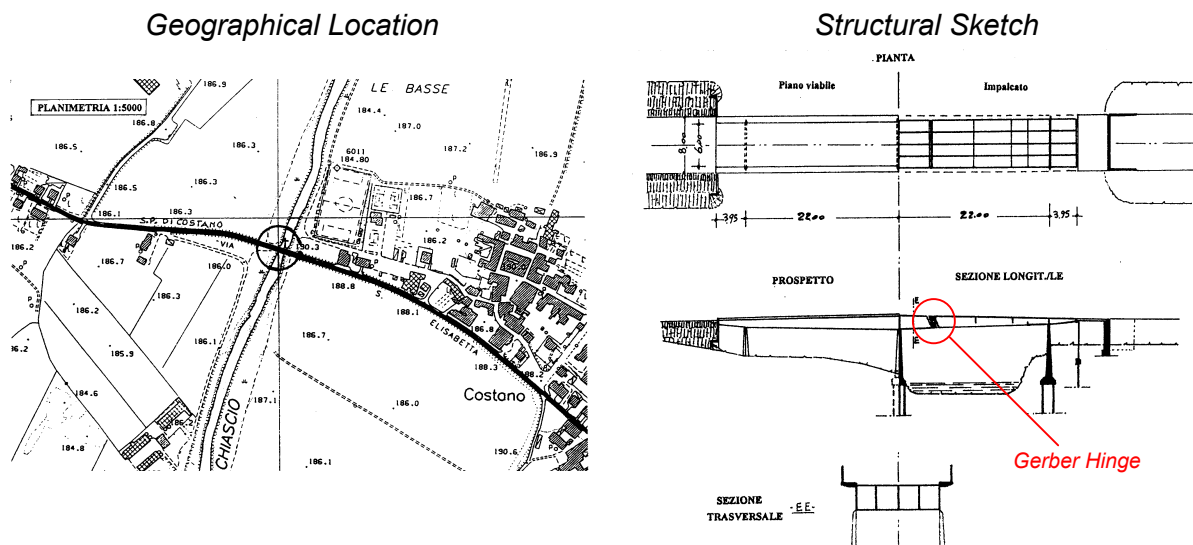


Fig. 6 - The "Costano" Bridge

The static scheme of the bridge is constituted by two decks, supported by three piers and linked by a Gerber hinge (fig.6). The bearing structure is a grid system, composed of five beams and an upper slab. Nevertheless, the box girder system, with a lower slab, was utilised near the piers and the Gerber hinge.

Geometrical survey and inspection

The original design documents (developed at the time of the construction) were no longer available. Therefore it was necessary to carry out a preliminary geometrical survey.

In order to estimate the strength of the concrete, experimental tests in site were performed. The characteristic strength of the concrete was estimated varying in 25-30 N/mm² range and the lower value was utilised in the check.

Moreover, in the cross sections at mid span versus Torgiano and in the upper slab at central pier, the concrete was scarified in order to find the tension reinforcement.

The longitudinal reinforcement was realised by smooth bars with 26 mm diameter.

For example, regarding the cross sections at mid span versus Torgiano, the following longitudinal reinforcement was found: 10 Ø 26 (+ 2 Ø 26 with hook) for internal beams and 13 Ø 26 (+ 1 Ø 26 with hook) for external beams.

Moreover the mechanical characteristics of steel were founded by laboratory testing performed on removed bars (the steel was assumed to belong at Fe B38 k class).

Dynamic Tests equipment

During the tests, various responses were measured with accelerometers and strain gauges.

In particular the testing equipment was composed of:

- four accelerometers: two of them were located at mid span versus Torgiano (at the lower part of central and external beams constituting the grid system) and the other two were located at both sides of the Gerber hinge (on the upper part of the deck);
- eight strain gauges: four on the steel bars (two at the mid span versus Torgiano in the lower part of the beams and two at the upper part of the deck over the central pier), four on the concrete (two at mid span versus Torgiano and two at span versus Costano on upper part of the deck).

In this paper Bridge structural response at mid span versus Torgiano has been analysed (Strain Gauge n.1 on steel bars in the lower part of the central beam and Accelerometer n.3 at the lower part of the same beam; fig.7b).

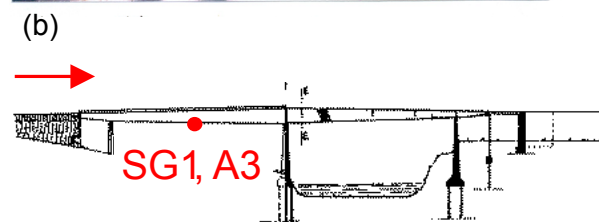


Fig.7 – Traffic loads testing

Traffic loads testing

Dynamic tests relative to the run of a single truck were performed (fig.7a).

Accelerometers and strain gauges (on steel bar and concrete) signal was recorded (Fig.8). The tests were repeated by varying the speed of the truck (slow speed, 30, 40 and 65 Km/h).

The obtained results showed that effectiveness of the Gerber hinge was compromise. This aspect confirmed the preliminary observation obtained during the inspection of the bridge.

Moreover, the bridge structural damping value was drawn from an analysis of the free oscillations of the bridge after the passage of a truck.

Moreover, by forced testing, natural

frequencies were determined; in particular, a first natural bending frequency in an interval of 4.15÷5 Hz, a second bending frequency in an interval of 7.3÷8.3 Hz and a third natural torsional frequency between 10.1÷12.3 Hz were found.

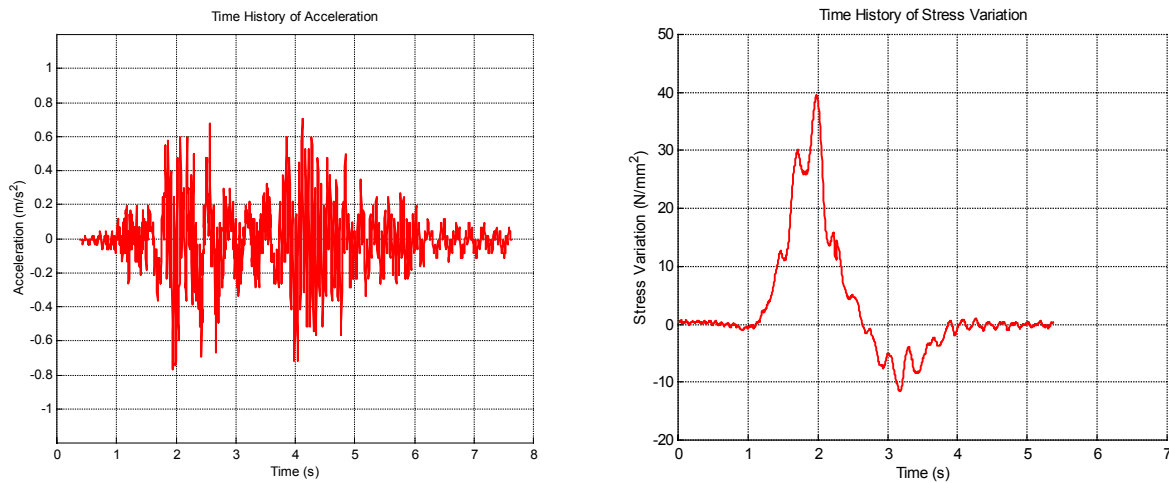


Fig.8 - Structural response of the bridge when truck is passing (65 Km/h); (a) acceleration A3 and (b) stress variation in steel bar SG1

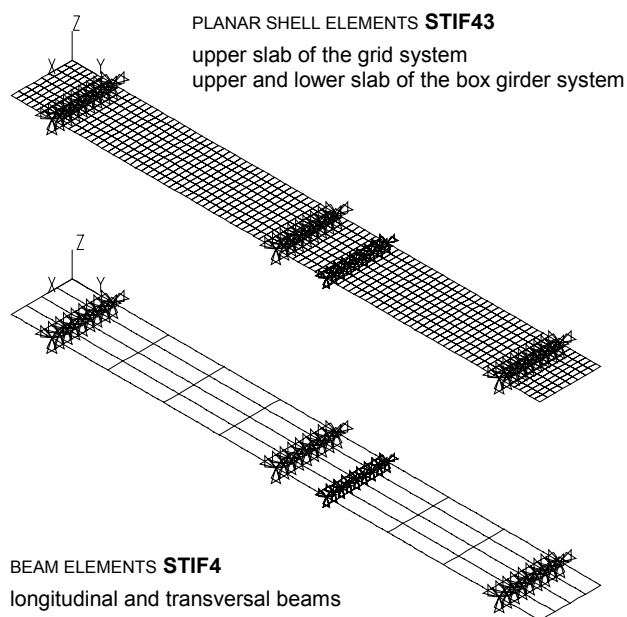


Fig.9 - FE ANSYS Model

Bridge Modelling

In order to evaluate the dynamic characteristics of the bridge and its response under specified loading and standard design loads, a numerical model was set up using the Finite Element technique (ANSYS software). The model of complete structure was composed of beam elements, which schematised the longitudinal and transversal beams, and planar shell elements, used for modelling the upper slab of the grid system and the upper and lower slabs of the box girder one, for a total of 882 nodes and 1344 elements. The model was checked by comparison among experimental displacements of static tests and those obtained by numerical analyses [1] and by comparison between experimental and numerical natural frequencies (Table 1).

To perform MB Simulations (modal analysis and transient analyses with moving truck) two desk FE submodel, delimited by Gerber Hinge, were considered. Two Modal neutral file were realised in FE environment (deck no.1 mnf model has 55 dofs and deck no.2 mnf model has 47 dofs); boundary dofs, for static correction modes, have been chosen considering Flex PTCV paths (22 connecting points) and global external and internal constraints (three pears and Gerber Hinge). The bridge flexible MB assembly has shown a good agreement with Experimental and FE results in terms of natural frequencies (Table 1).

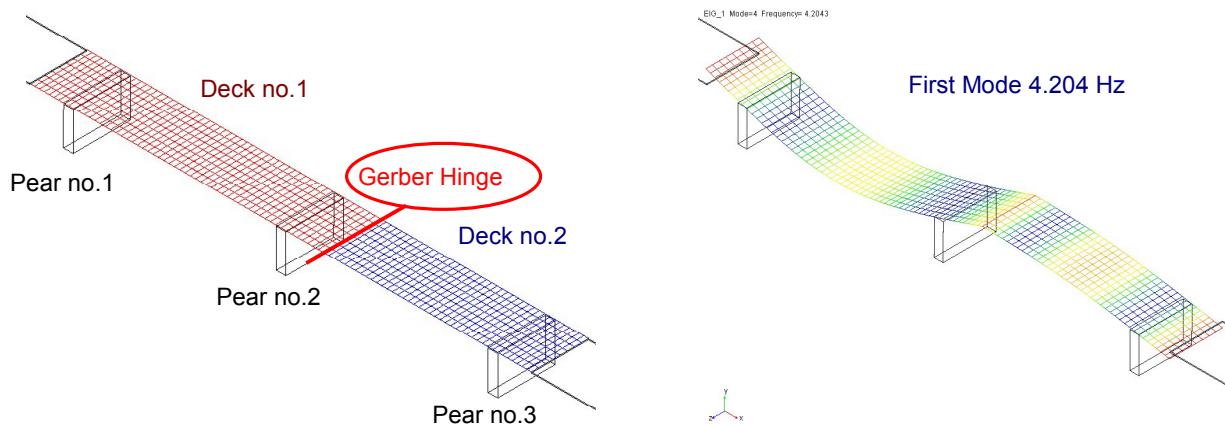


Fig.10 - MB bridge model and 1st constrained natural mode

Table 1

Comparison among experimental and numerical (FE and MB) bridge natural frequencies

Mode	Experimental Testing	Numerical Model	
		FE	MB
1 th	4.15÷5 Hz	4.19 Hz	4.20 Hz
2 th	7.3÷8.3 Hz	7.84 Hz	7.77 Hz
3 th	10.1÷12.3 Hz	13.53 Hz	13.30 Hz

Moving truck simulations

To perform moving truck simulations a Truck model was realised (Fig. 11). A three independent axle vehicle was set up according with test truck characteristics (Fig.7a).

Simulations were realised by varying the speed of the truck (slow speed , 30 and 65 Km/h) according to experimental tests and they have been run with a sampling frequency of 100 Hz.

Dynamic traffic tests and relative MBS simulations are reported and compared in terms of acceleration (Fig.12 and Fig 13).

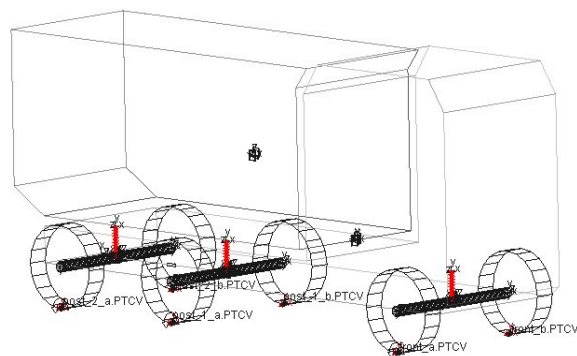


Fig. 11 - Truck MB model

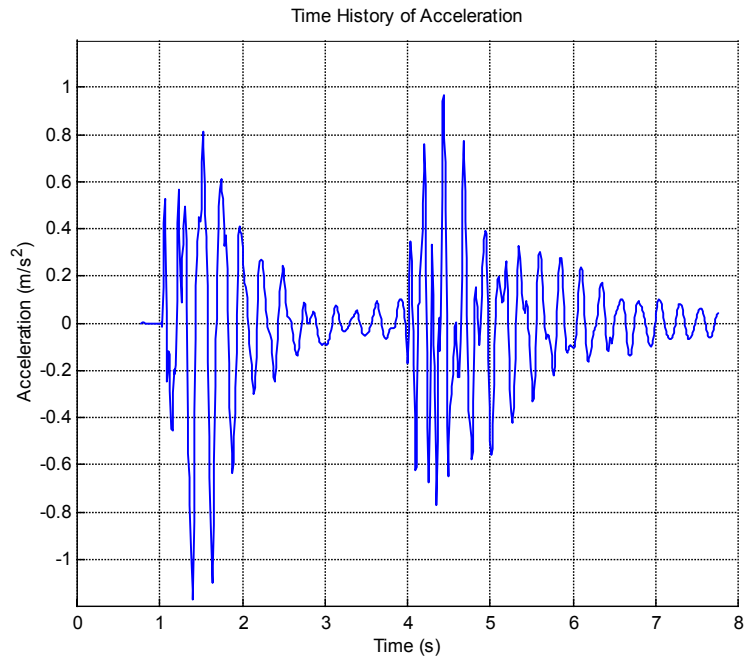


Fig.12 - MBS acceleration time history at A3 location – 65 Km/h

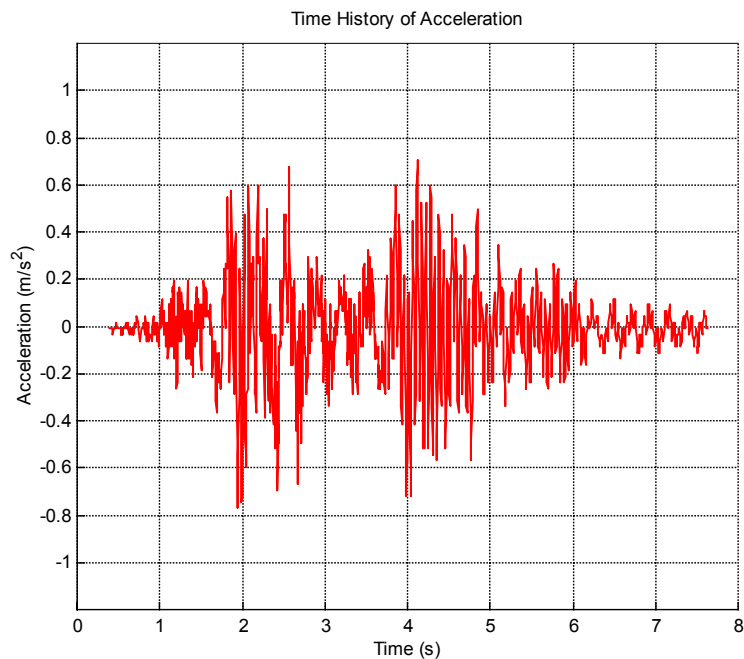


Fig.13 - Test acceleration time history at A3 location – 65 Km/h

Moreover, using a new Stress Recovery procedure implemented by the authors for a particular MBS/FEM (ADAMS/ANSYS) environment [2], a comparison was realized between stress test measurement and numerical one at SG1 location. Using time history of bending moment on beam elements resulting by Stress Recovery procedure, concrete beam theory and inspection results, stress time histories at the lower part of the central beam were obtained (Fig.14).

The comparison between test and MBS acceleration results shows how Flex PTCV methodology is a good approach for moving parts on flexible body simulation. In particular stress comparison shows a good agreement between experimental and numerical results both from qualitative than from quantitative point of view (Fig.14).

Moreover, taking into account the stress variation in steel and concrete, while varying the truck speed, the dynamic amplification factor (DAF) was estimated equal to 1.1 in perfect agreement with test results.

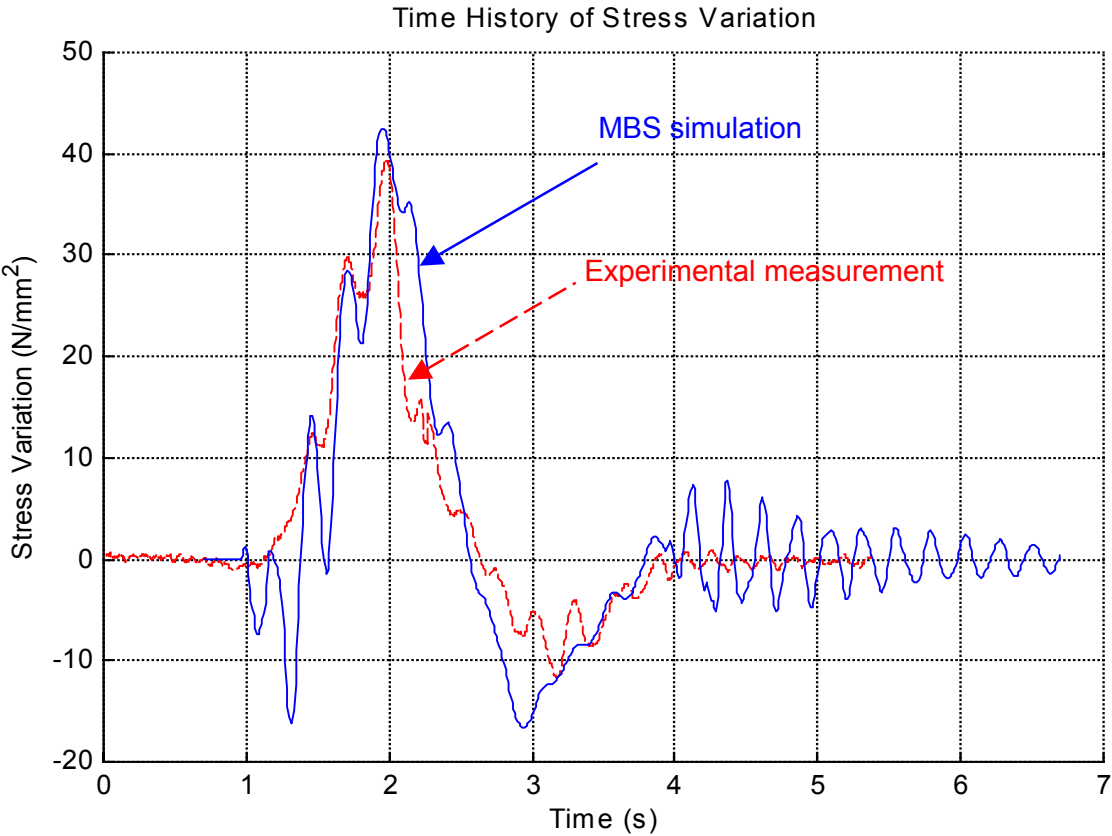


Fig.14 - Comparison between experimental and MBS stress time history at SG1 location - Truck velocity of 65 Km/h

CONCLUSIONS

In this paper a new MBS tool, implemented by the authors in ADAMS environment, allowing the simulation of moving parts on flexible bodies, has been shown.

A test case considering traffic testing on a reinforced concrete highway bridge is illustrated. This application example has demonstrated how this new tool allows to simulate with a good agreement the behavior of concrete bridge under moving loads and/or moving mechanical systems (i.e. truck characterized by three independent axles). In this particular case dynamic traffic tests and relative MBS simulations were reported and compared in terms of acceleration. Moreover, using a new Stress Recovery procedure implemented by the authors for a particular MBS/FEM (ADAMS/ANSYS) environment, a comparison was realized between stress test measurements and numerical ones. All these results and in particular stress ones show a perfect agreement between numerical and experimental ones.

REFERENCES

- 1) Cianetti F, Gusella V., "Dynamic tests and identification of a reinforced concrete highway bridge", Proceeding of the Third Conference on Structural Dynamics – Eurodyn '96, Florence, Italy, 1996;
- 2) Braccesi C., Cianetti F., Ambrogi F., "State of stress evaluation of structural elements by modal synthesis", Proceedings of 15th ADAMS European User's Conference, Rome, 2000;
- 3) Paultre P. et al., *Dynamic Testing Procedures for Highway Bridges Using Traffic Loads*, Journal of Structural Engineering, Vol. 121, No.2, pp. 362-376, February, 1995;
- 4) Salawu O. & Williams C., *Bridge Assessment Using Forced-Vibration Testing*, Journal of Structural Engineering, Vol. 121, No.2, pp. 161-173, February, 1995;
- 5) Shabana A.A., "Dynamics of multibody systems", John Wiley & Sons, 1998;
- 6) R.R. Craig, M.C.C. Bampton, "Coupling of substructures for dynamic analyses", AIAA Journal, vol. 6, n.7, 1968.

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Roma, 15-17 november 2000

"Simulation of moving parts on flexible body using multibody approach. Test case on a reinforced concrete highway bridge"

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Agenda

■ *Flexible PTCV tool in ADAMS*

- ◆ *Motivations*

- ◆ *Implementation*

- *Flex PTCV topology*
- *Force*

■ *Test case on a highway concrete bridge*

- ◆ *Dynamic experimental tests*

- ◆ *FE model*

- ◆ *MB model*

- *Dynamic analyses*
- *Stress recovery*



Flex PTCV tool motivations

- *CMS of flexible bodies*

- ◆ *Normal constrained modes*
- ◆ *Static correction modes*

- *In ADAMS:*

- ◆ *Relative position of standard curve points can't change during simulations*
- ◆ *FBs do not allow floating markers belonging to them*

- *Need for a new element allowing a part to move along a FB*



Flex PTCV tool implementation (1)

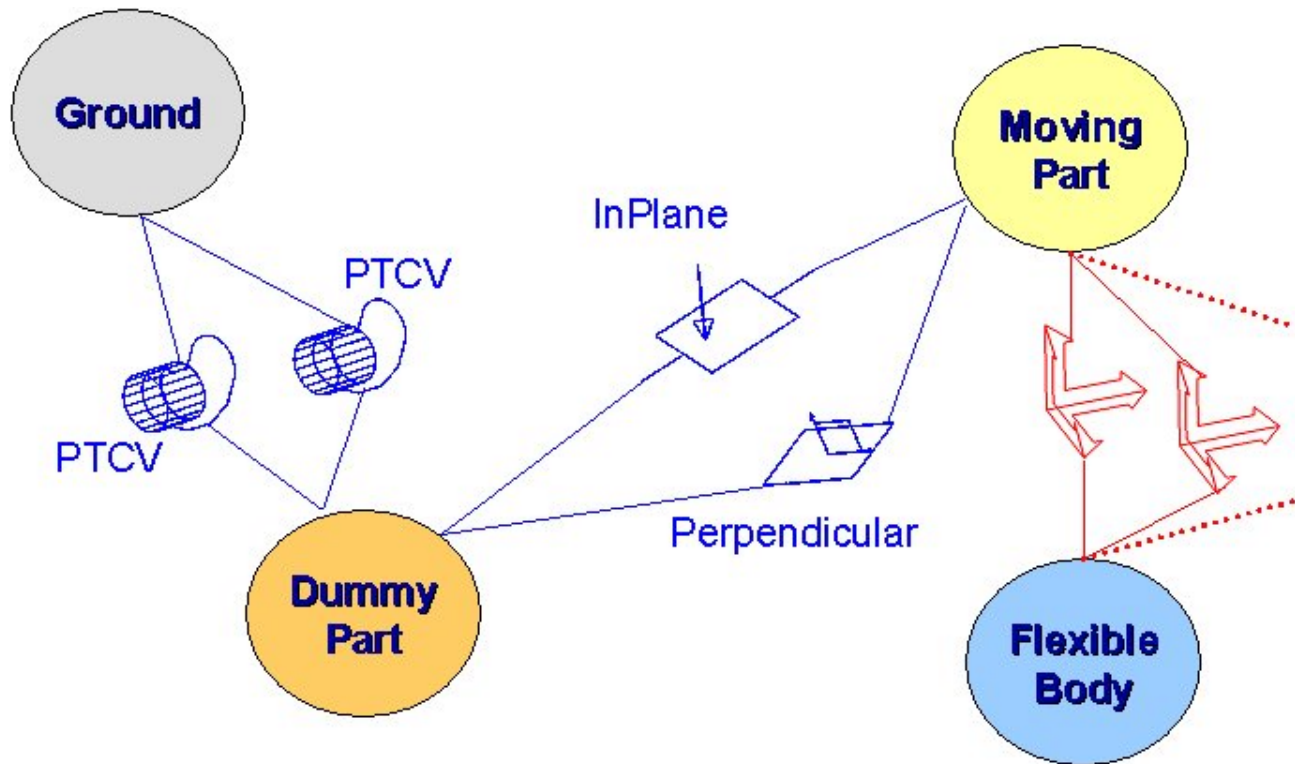
- *Forces on the FB (Vector Forces)*

- *Definition of motion along the FB*
 - ◆ *User defined curve statement (spline along FB points)*
 - ◆ *Dummy part effectively following the curve (kinematically)*

- *Contact algorithm featuring back-lash*

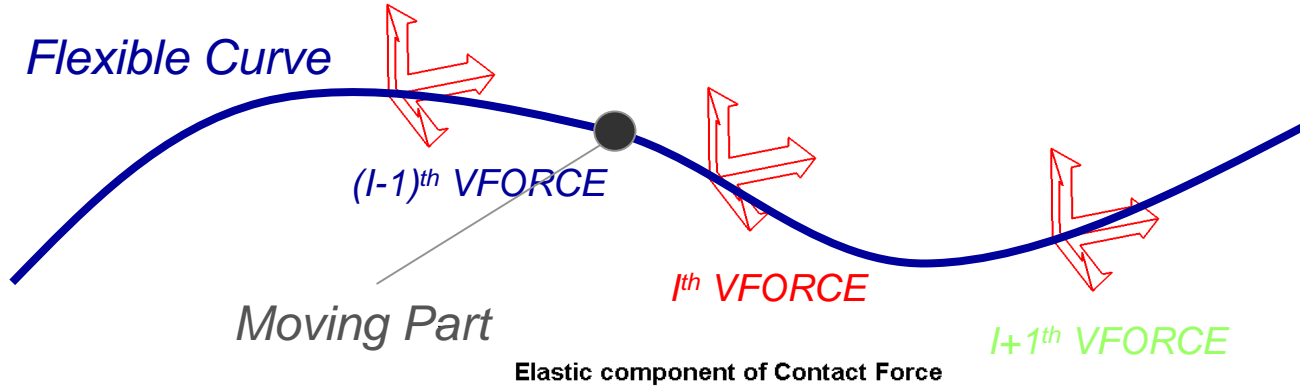
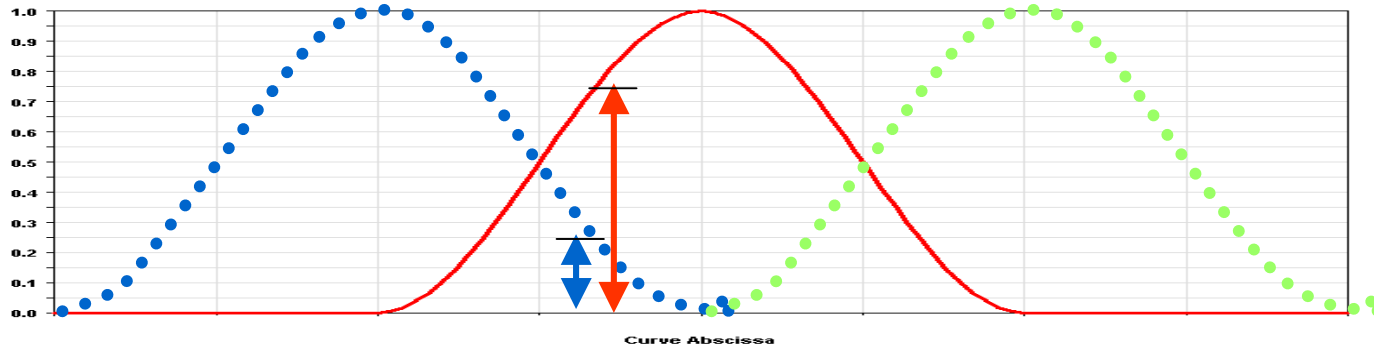


Flex PTCV tool implementation (2) (UDE topology)

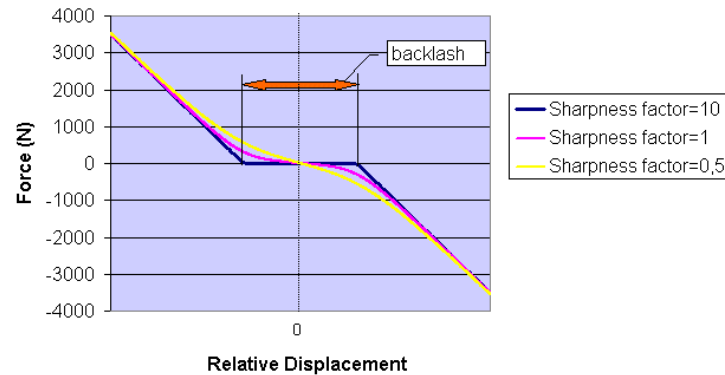


Flex PTCV tool implementation (3)

(Force shape function)

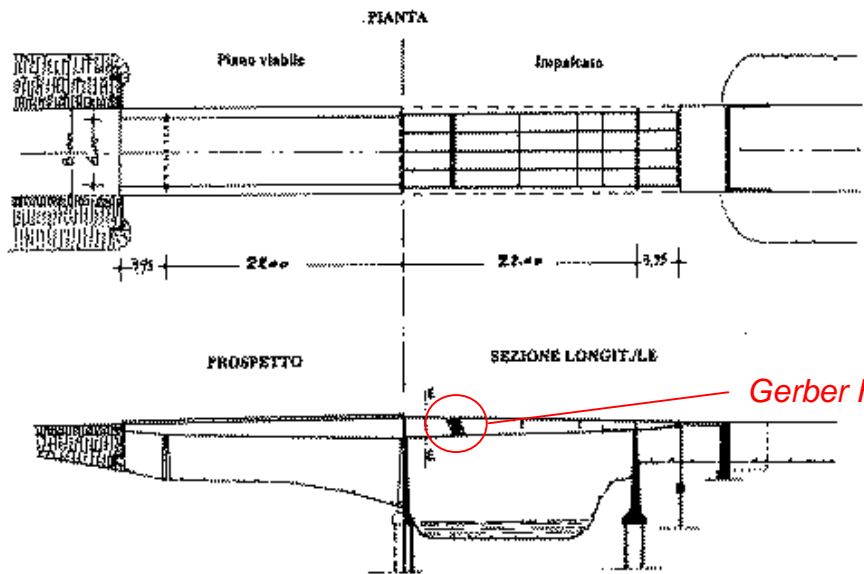
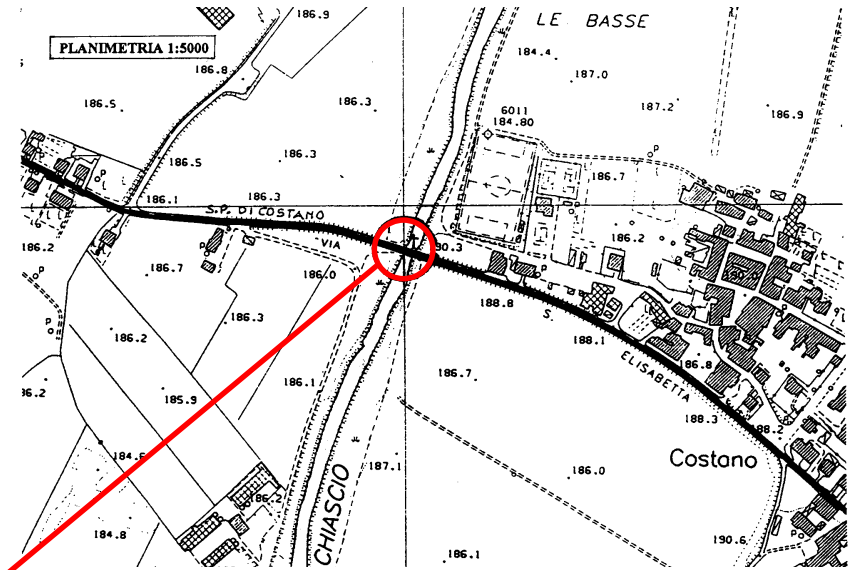


Elastic component of Contact Force



TEST CASE: traffic tests and simulations on the "Costano" bridge

Geographical Locations



SEZIONE TRASVERSALE E.C.

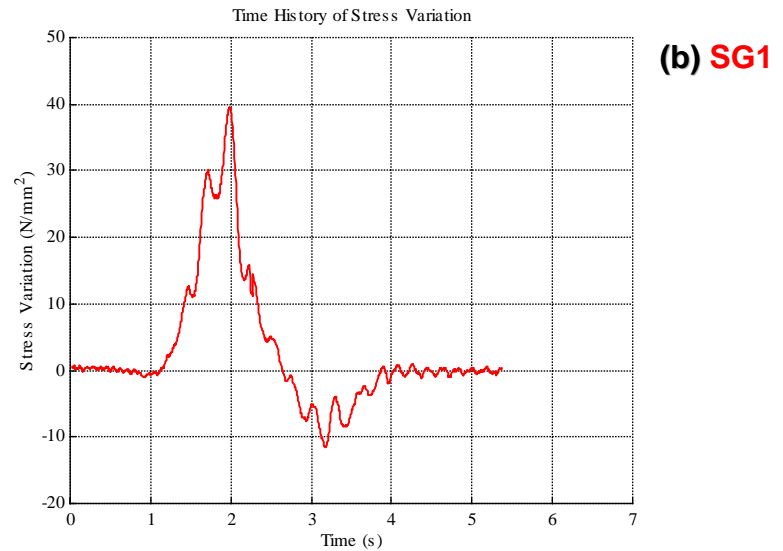
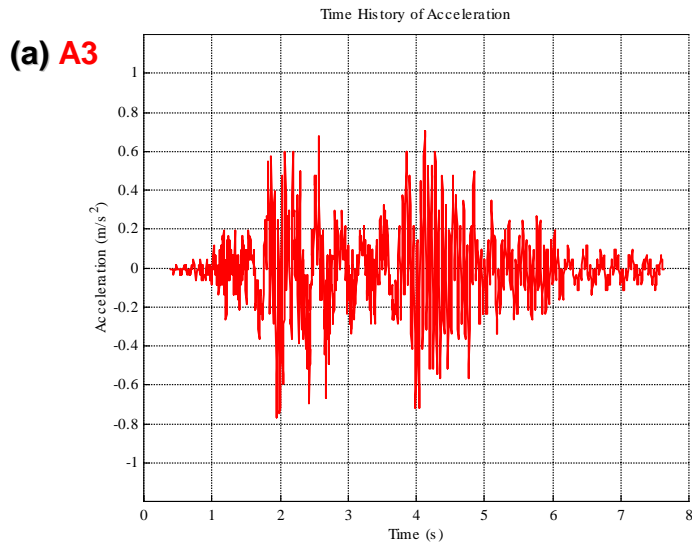
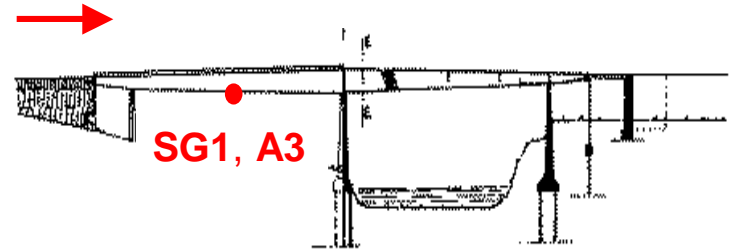


Structural Sketch



Dynamic Tests

(Moving loads)



Structural response of the bridge when truck is passing (65 Km/h)
(a) acceleration A3 (m/s^2) and (b) stress variation in steel bar SG1 (N/mm^2)



Numerical Model

(ANSYS FE model and ADAMS MBS model)

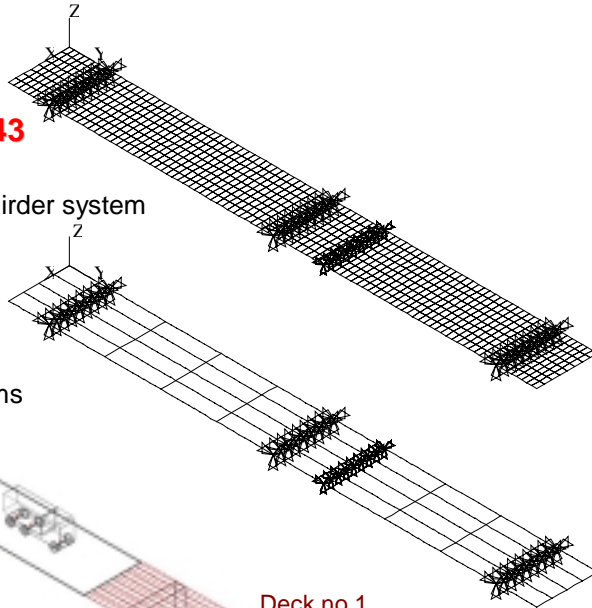
FE model

planar shell elements **STIF43**

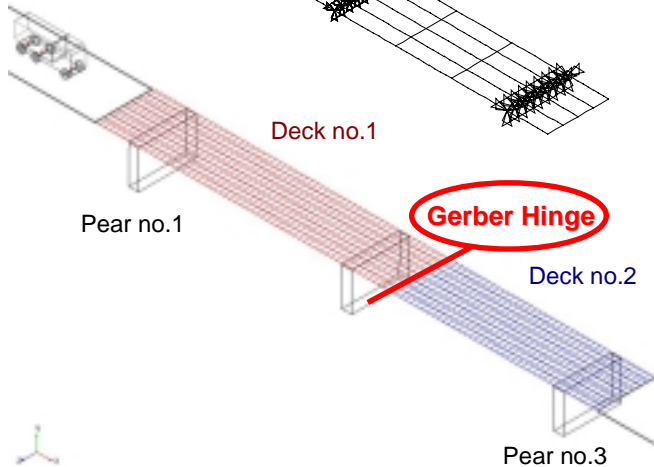
upper slab of the grid system
upper and lower slab of the box girder system

beam elements **STIF4**

longitudinal and transversal beams



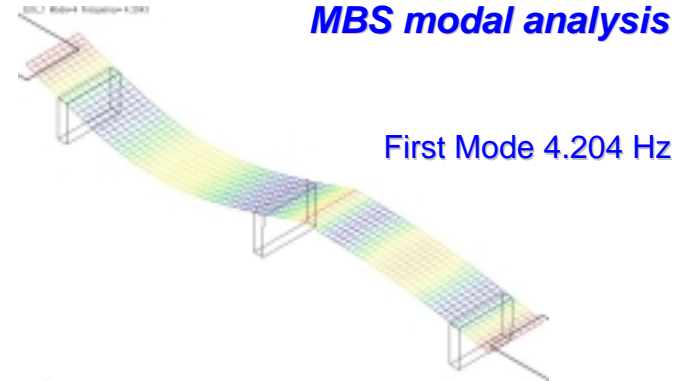
MBS model



Comparison among experimental and numerical (FE and MB) bridge natural frequencies

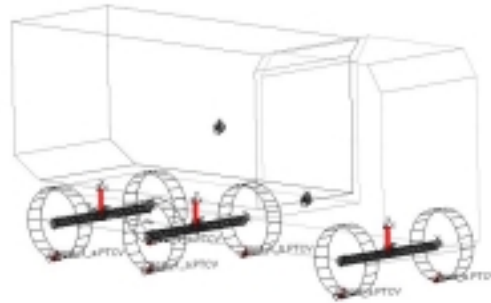
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MBS modal analysis



MBS Analyses

(traffic simulations)



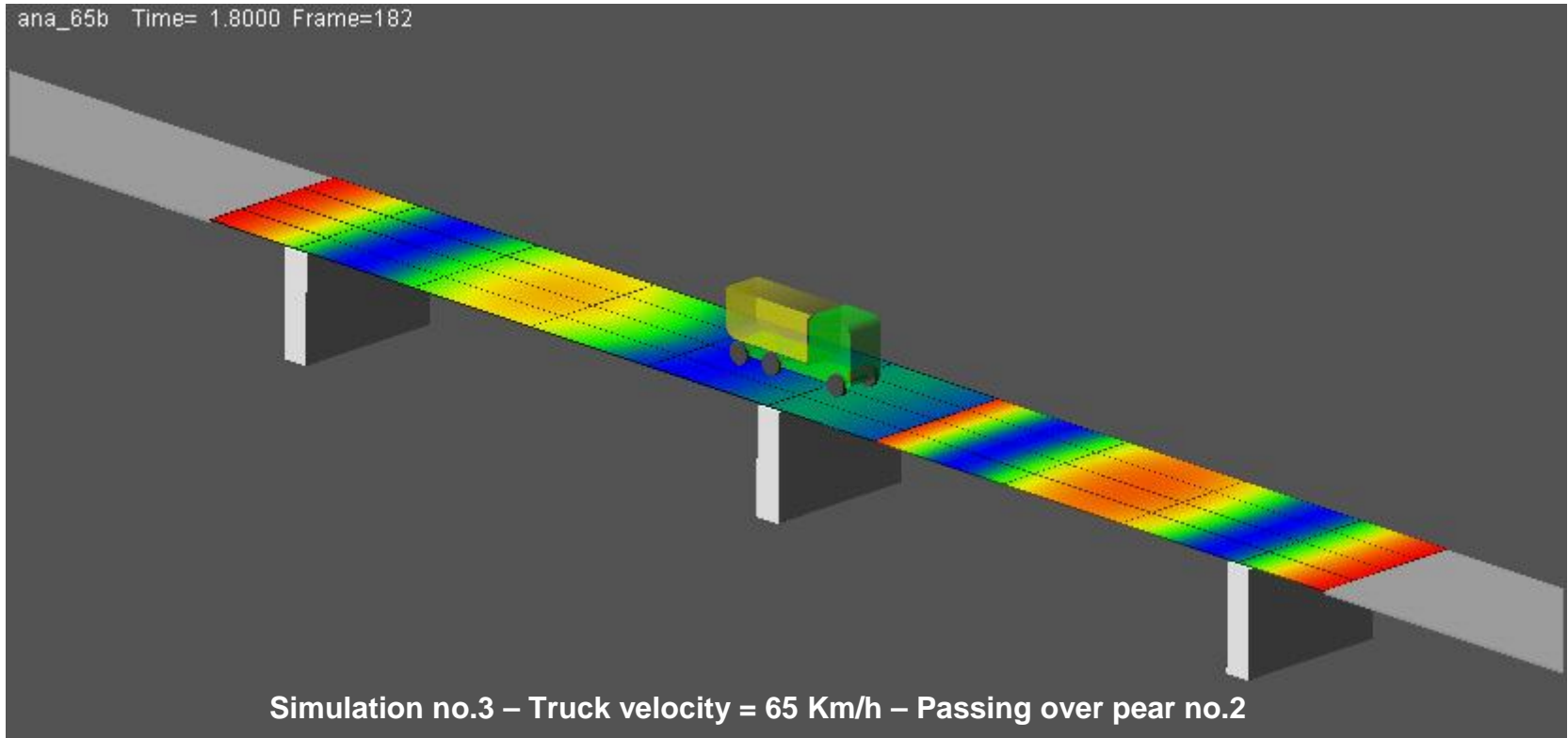
Truck MB model

- Slow velocity
- 30 Km/h
- 65 Km/h

Truck Model Velocities

100 Hz

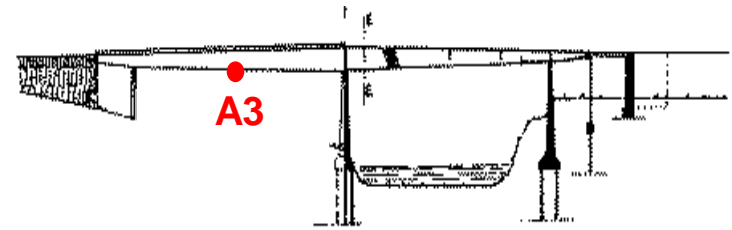
Sampling Frequency



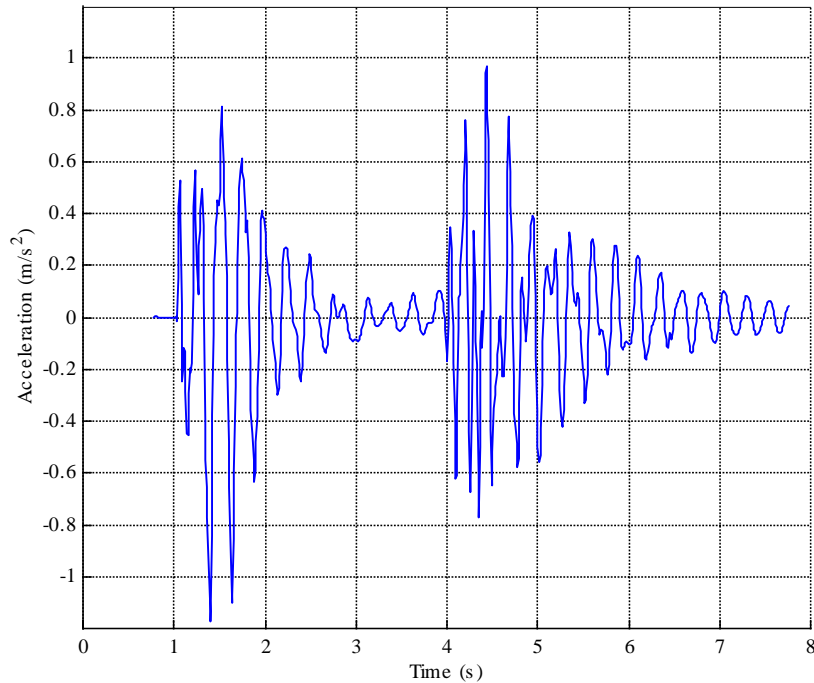
MBS Analyses Result

(comparison between MB and TEST results)

Acceleration results (truck velocity = 65 Km/h)

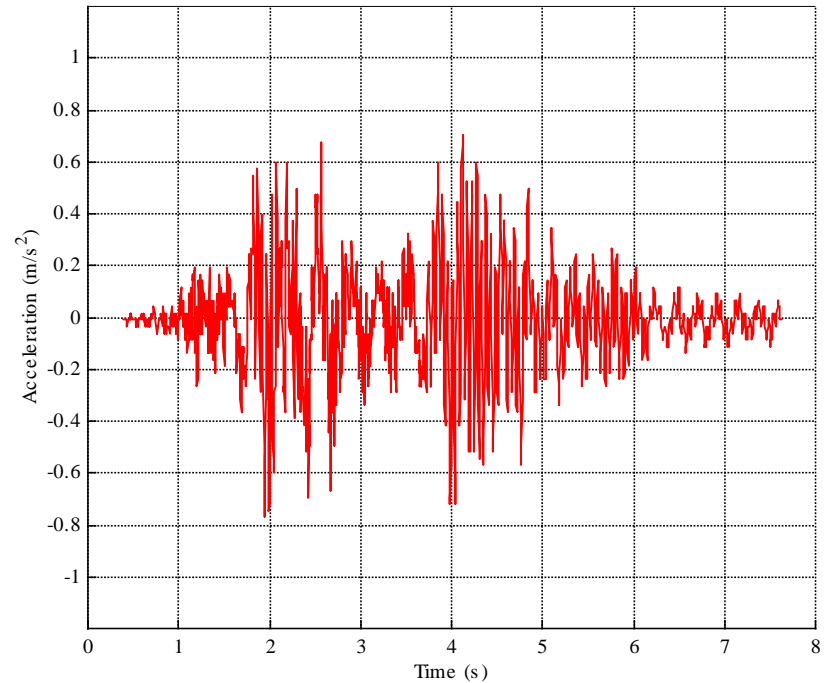


Time History of Acceleration



MBS acceleration time history at A3 location
(lower part of the central beam)

Time History of Acceleration



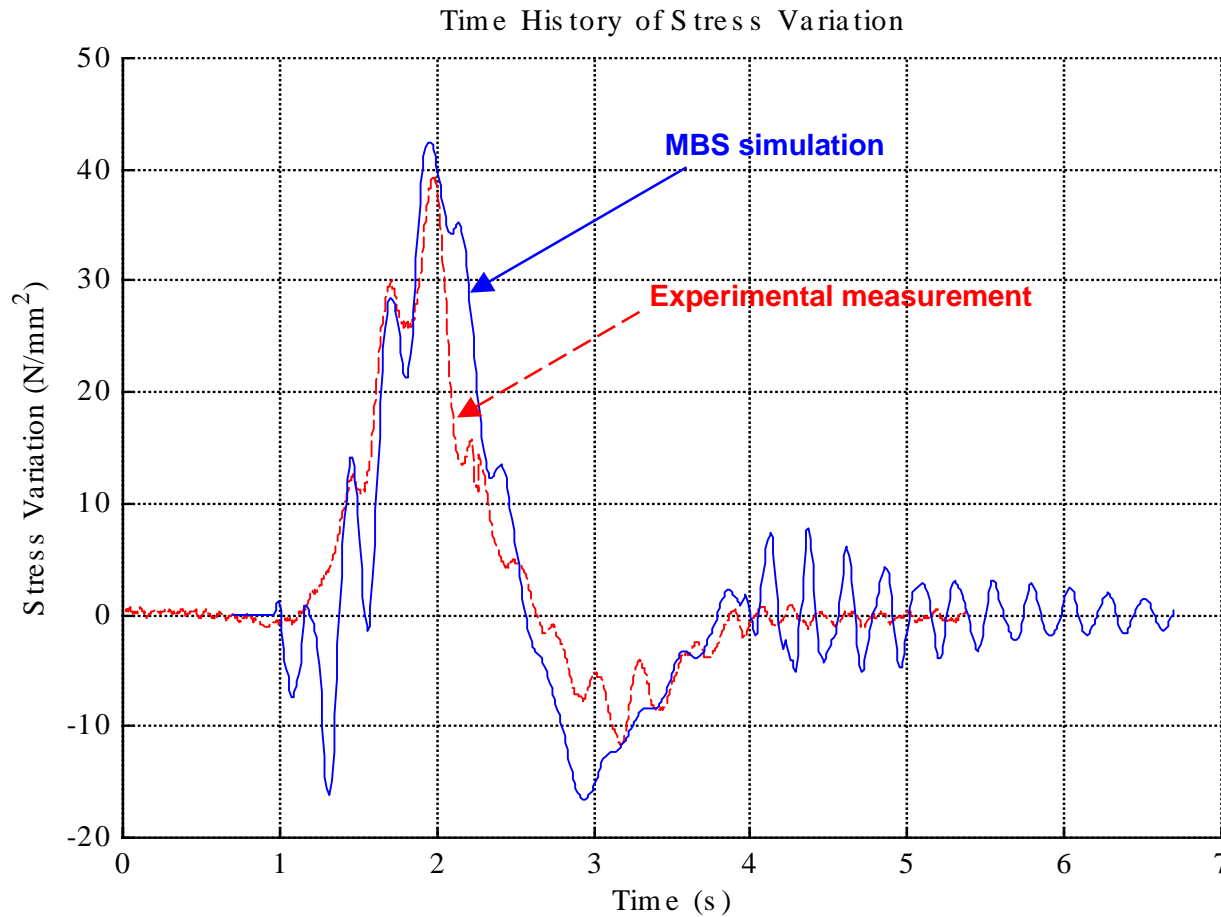
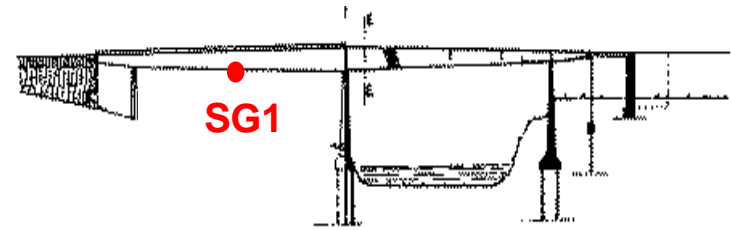
Test acceleration time history at A3 location
(lower part of the central beam)



MBS Analyses Result

(comparison between MB and TEST results)

Stress results (truck velocity = 65 Km/h)



Stress time histories at SG1 location (steel bars at the lower part of the central beam)



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