EFFECT OF FLUID-STRUCTURE INTERACTION ON CONNECTION FORCES IN BRIDGES DUE TO TSUNAMI LOADS

Denis Istratii[1], Ian G Buckle[2]

Abstract

In this study, advanced fluid-structure interaction (FSI) analyses are described in order to examine the role of computational fluid dynamics and structural dynamics in determining the tsunami forces on the connections of a bridge. Equivalent 2D analyses were conducted with LS-DYNA considering the flexibility of both the superstructure and the connections. Both the superstructure and substructure flexibility were found to significantly influence the external tsunami loads on the bridge and the connection forces. In addition, it affected the distribution of the forces in the connections which indicated the significance of the dynamic characteristics of the bridge.

Introduction

The 2004 Indian Ocean Tsunami and the 2011 Great East Japan (Tohoku) Tsunami caused an unprecedented number of casualties and widespread damage. During these catastrophic events numerous bridges were destroyed, cutting lifelines and access roads to coastal communities hit by the tsunamis. These unfortunate events demonstrated the vulnerability of highway and railroad bridges to tsunami hazards and the need for developing tsunami-resilient bridges in coastal areas.

The academic community from round the world has responded to this need and several studies have been published in recent years. In particular, ocean engineers and structural engineers embarked upon a joint venture to understand the physics of tsunami waves and their effects on structures. The first studies were based mostly on experimental work, while numerical work emerged later. Some of the experimental studies investigated tsunami loads on decks with girders (Lau et al (2011), Maruyama *et al* (2013), Hayatdavoodi *et al*, Part II (2014)), box- shaped decks (Hayashi (2013)) and flat slabs (Seiffert *et al*, Part I (2014)). In most of these experiments, the researchers constructed their bridge models from acrylic, wood or steel and they either supported the deck rigidly from top/bottom of the deck or allowed the deck to move freely on the supports. Furthermore, they were all very small-scale experiments with scale factors ranging from

[1]Grad Assistant,Dept of Civil and Environmental Engineering, MS258, University ofNevada Reno
[2] Professor, Dept of Civil and Environmental Engineering, MS258, University of Nevada Reno

1:100 to 1:35. Due to their small size, scale effects are expected to be significant and the model structures are expected to be stiffer than the prototype ones, as explained by Martinelli *et al* (2011). Therefore, the flexibility of the prototype is most likely not scaled correctly, even in the experiments where both the deck and the piers are modeled.

Recently, Hoshikuma *et al* (2013) conducted the largest, to date, scaled experiment on tsunami effects on bridges. Their experiment was at a scale of 1:20 and examined several different cross-sections,in an attempt to give insight into the forces that various types of bridges have to withstand. In this experiment the specimens were made of acrylic or wood and they were connected rigidly to a pier at the middle of the superstructure. Thus, the flexibility of the connections between the superstructure and substructure was not modeled (since it was not feasible to do so at such a scale). In addition, the mass of the model was negligible compared to the mass of the wave that impacted it, which means the inertia forces in the bridge are very small and the dynamic behavior of the bridge is not correctly modeled in this experiment.

Apart from the experimental studies, several numerical analyses have been conducted to study tsunami force effects on bridges. Among others, Lau *et al* (2011) conducted CFD analyses using FLOW 3D, Hayatdavoodi *et al* (2014) and Bricker *et al* (2012) used OPENFOAM, and Kataoka *et al* (2013) used CADMAS-SURF. In the first two cases, the researchers tried to match the CFD analyses with their experimental results. In the latter two cases, the researchers took the tsunami effects (stresses, forces, moments) directly from the CFD analyses, which considers the structure as a rigid boundary and calculates the forces from integration of pressures, and compared their results with the bridge capacity, in an attempt to explain the failure/survival of certain bridges during the Tohoku Tsunami 2011. Another research group (Yim *et al* (2011)) conducted numerical studies with a FEM-based multi-physics software program called LS-DYNA. The advantage of using multi-physics software like LS-DYNA, compared to pure CFD software, is that it can solve the equilibrium of the structure and its response at the same time as water flow, while the disadvantage is generally the associated high computational cost.

In order to avoid this cost Yim *et al* (2011) modeled the structure with a rigid material, sitting on pinned supports, and calculated the applied tsunami loads. Last but not least, Murakami *et al* (2012) calculated the pressures from the CFD software CADMAS-SURF/3D and then re-applied these pressures as external loads on a flexible fiber-model bridge, sitting on bearings represented by elasto-plastic springs. This approach is an improvement over previous studies, since it models both the flexibility of the deck and the flexibility of the connections and thus distributes the external tsunami load to the connections accordingly. However, it still neglects the flexibility of the bridge and its dynamic characteristics when calculating tsunami loads using CFD software, which means the level of accuracy in the calculated external tsunami loads is not known.

Objective of the Study

The above literature review demonstrates that there have been several interesting studies so far, that have contributed substantially towards understanding tsunami effects on bridges. However, the role of the bridge flexibility has not been studied, mainly due to the widespread belief of many researchers, that CFD analyses with rigid structures give conservative estimates of tsunami loads, and the high computational cost of including flexibility (fluid-structure-interaction) in these analyses. Also, the state-of-the-art in multi-physics software is immature and requires expertise in both wave and structure modeling when conducting such simulations.

Experience with other types of dynamic loading, such as earthquake and wind, has shown that the flexibility and generally the dynamic characteristics of the structure (mass, damping), will substantially affect the load that the structure has to withstand. Therefore, in this study, the objective is to model explicitly the flexibility of the superstructure and its connections, and investigate the dependence of tsunami loads on bridge flexibility, especially during the first impact of the wave, which is a transient phenomenon. For this purpose, we will conduct fluid-structure interaction analyses using LS-DYNA.

Fluid-Structure-Interaction (FSI)

Fluid-structure interaction (FSI) is the interaction of a movable or deformable structure with a fluid flow (Bungartz (2006)). In particular, FSI is traditionally considered a two-way coupling where the structure is affected by the pressure and/or viscous forces of the fluid, while the fluid is influenced by the shape of the structure and its velocity (CD-Adapco (2013)). This two-way coupling can be either “strong” or “weak/loose” depending on the specific application. According to the above manual, the “strong” (or alternatively called “implicit”) coupling is required for “dynamic” or “transient” simulations and in cases where relatively light or compliant structures interact with a relatively heavy fluid. On the other hand, “weak” coupling is generally appropriate for “static” or otherwise steady-state solutions where the velocity of the structure is close to zero. However, in many applications it is not clear in advance which type of coupling is required and analysts should try both.

A number of computer programs are available to conduct FSI analyses to various degrees of accuracy, among which are the following: Abaqus, AcuSolve, ALGOR, ANSYS, COMSOL, LS-DYNA, MscNASTRAN, OpenFOAM and STAR-CCM/STAR-CD.

Since the concept of fluid-structure interaction is very recent, many codes are still not fully developed or fully validated and therefore the user should be cautious and aware of the limitations of each numerical tool.

FSI Using LS-DYNA

In LS-DYNA there exist various solvers that can be used to study FSI effects. One of those - the ALE solver- is usually recommended for short duration and highly transient phenomena such as explosions, where the fluids are compressible. This method combines the Lagrangian and Eulerian method in the same model and it allows for the fluid material to flow through the elements (Souli 2009). FSI is handled through a coupling algorithm which can be constraint-based or penalty-based. One of its limitations is that it is applicable only to laminar flow. It cannot account for fluid boundary layer effects (drag) because it does not solve the full Navier-Stokes equations (LS-DYNA AWG 2013). In addition, the method is generally appropriate for very short duration phenomena since it is an explicit algorithm that uses a very small time step (usually in the range of 10^{-5} to 10^{-9} sec) which is automatically defined based on the element size and speed of sound in the specific material.

Experience has shown that the ALE solver canalso be sensitive to the penalty coupling spring, the stiffness of which can create inaccurate results, introduce instabilities and reduce the time step. Therefore, the user should try to find the most appropriate value for the penalty stiffness and make sure the results are not dependent on the chosen value. Last but not least, the ALE solver is also sensitive to the number of elements and mesh size and even when a stable solution has been established, a minor change can create instabilities. Due to these factors, a stable solution that is independent of the mesh size and the penalty stiffness, for relatively long duration phenomena (in the range of seconds) such as the impact of tsunami waves on bridges, is computationally very expensive. However, the advantage is that the solver uses a monolithic approach and can capture the compressibility effects of the fluids.

Numerical Model

The numerical studies described below used a model based on the dimensions of the Utatsu Bridge, which was one of the bridges that failed during the Tohoku Tsunami in 2011. The bridge had three different types of spans, with different cross-section depths and different number of girders. In this study we used a concrete I-girder section similar to the one of the spans S8-S12. Based on available evidence, a superstructure width of 8.25m, height of 2.1m, and a girder thickness of 0.3m was estimated.

Three dimensional FSI analyses should be conducted to rigorously study the interaction of tsunami waves with a bridge structure. However, it is generally common practice in CFD analyses to conduct 2D analyses before moving to 3D. This is because 2D analyses are much faster and can give an idea of what to expect from the more advanced 3D analyses. The 2D analyses also serve as a rational check for the 3D analyses. However, in this study, although the ALE method in LS-DYNA has a 2D formulation, it was decided to use the 3D formulation, and the whole cross-section in X-Z was modeled along with a slice of finite length in the Y direction. In other words, an equivalent 2D model was analyzed, using 3D solids elements instead of shells that would be normally used in 2D analyses. For the bridge both *MAT_ELASTIC and *MAT_RIGID were used, while for the water and air *MAT_NULL was used.

Since the goal of this study was to investigate the interaction of the bridge with the waves and the role of the bridge flexibility, particular attention was given to the flexibility of the deck and the flexibility of the connections (bearings). The bearings were modeled as translational uncoupled springs with a horizontal stiffness of 875KN/m and a vertical stiffness of 8.75 x10^5 KN/m. Using the above cross-section, four different cases were modeled: (i) a rigid superstructure with pin supports (RP), (ii) a rigid superstructure supported on springs (RS), (iii) a flexible superstructure with pin supports (FP), and (iv) a flexible superstructure supported on springs (FS). All models used Rayleigh viscous damping assuming 5% damping in the first two modes. In order to reduce the computational time of the analyses the full development of the tsunami wave was not simulated, as it would probably be done in a pure CFD analysis.In addition, since the focus of this paper is not to provide equations for tsunami loads, but rather to look at the dynamic response of the structure when impacted by a wave, two simplified models for the wave were used. In the first model, an incoming volume of water was assumed with an initial velocity of 7m/s that reached the top of the bridge, and in the second and largest model,the wave was simulated by a dam break which allowed the software to calculate, automatically, the height and velocityof the wave at the location of the bridge. Since it has been seen in the aforementioned literature (Yim*et al.* 2011) that there is a high amplitude and short-duration force at the time of the initial impact of the wave on the structure, it was decided to focus only on the initial impact, to study the most significant effects of transient dynamics.The two different models are shown in Figures 1 and 2.

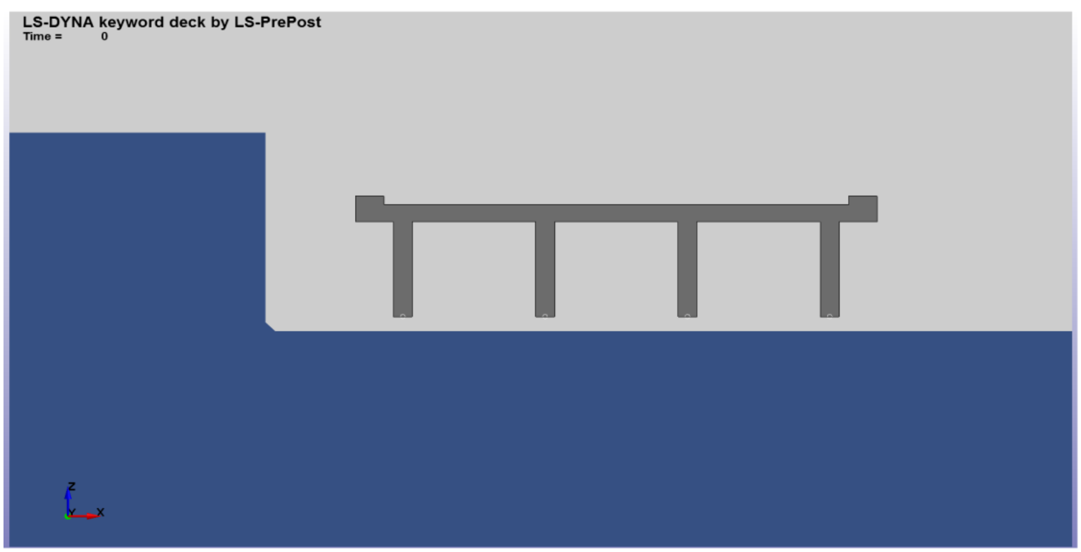

FIGURE 1: SIMPLIFIED MODEL 1

FIGURE 2: SIMPLIFIED MODEL 2 – DAM BREAK

Results and Discussion

In order to understand the dynamic behavior of the equivalent 2D model a modal analysis was conducted prior to the FSI analyses. The first ten modal periods are shown in Table 1 and the first four vibration modes are shown in Figures 3 and 4, for the flexible deck with pins and springs respectively. As can be observed from the table, the flexible deck with springs, is the most flexible case and has the longest modal periods, as expected.In addition, it will be seen that the first 10 modes have periods in the range of 0.1 sec to 0.004 sec which are generally small numbers. However, since the largest time-step used in the FSI analyses is around 10^{-5}sec, this means that the dynamic effects of all ten modes can be captured.

In the discussion below, the girder from the left, which is the first girder to be impacted by the tsunami, is referred to as girder No. 1, the right end girder as No. 4, while girders No. 2 and No. 3 will be the interior ones.

TABLE 1: MODAL PERIODS

Modal periods (sec) of 2D equivalent strip used in ALE FSI analyses			
	Rigid deck &springs	Flexible deck & pins	Flexible deck & springs
Mode 1	9.67E-02	5.91E-02	1.12E-01
Mode 2	9.84E-03	1.04E-02	2.62E-02
Mode 3	9.66E-03	9.84E-03	2.50E-02
Mode 4		8.00E-03	2.13E-02
Mode 5		6.44E-03	1.75E-02
Mode 6		6.29E-03	1.11E-02
Mode 7		5.97E-03	1.07E-02
Mode 8		5.01E-03	1.03E-02
Mode 9		4.68E-03	9.51E-03
Mode 10		4.49E-03	8.48E-03

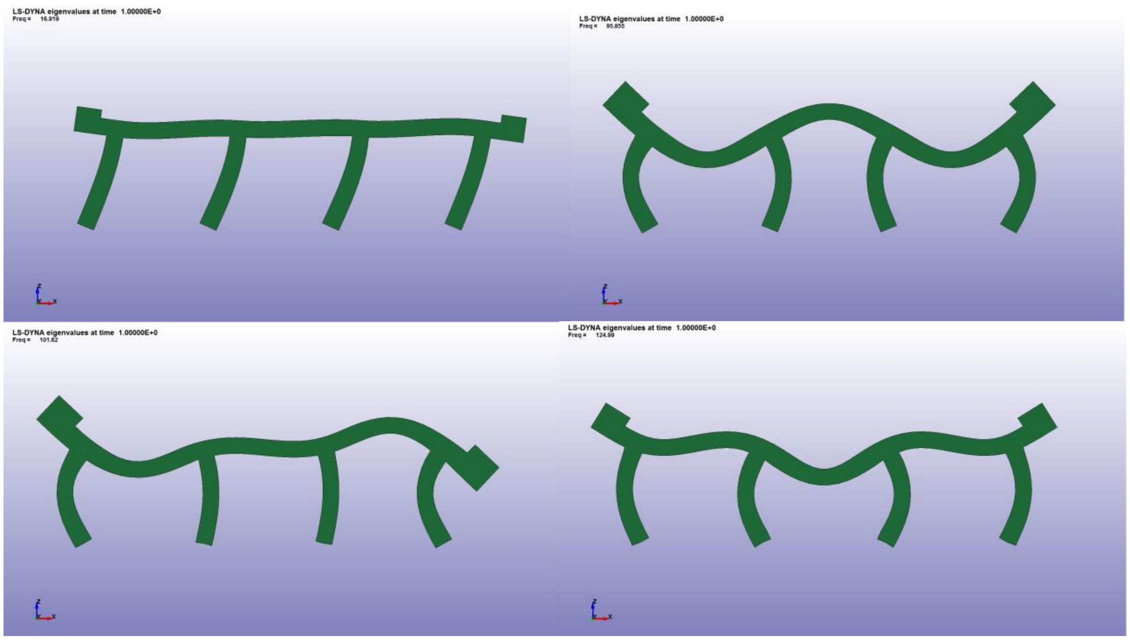

FIGURE 3: FIRST FOUR VIBRATION MODES OF A FLEXIBLE SUPERSTRUCTURE WITH PINNED (RIGID) CONNECTIONS (FP)

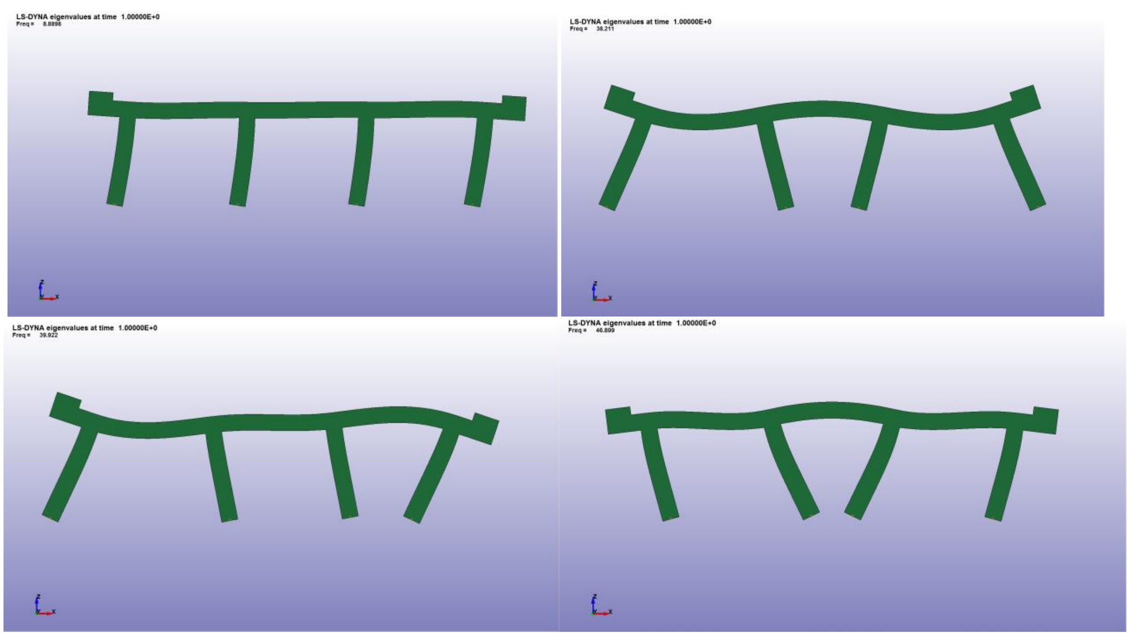

FIGURE 4: FIRST FOUR VIBRATION MODES OF A FLEXIBLE SUPERSTRUCTURE WITH SPRING (FLEXIBLE) CONNECTIONS (FS)

As noted above, FSI for the two model bridges was investigated using LS-DYNA. Figure 5 is a screenshot from one of the simulations showing the status of wave-bridge interaction for Model 2 at times of 1.8, 5.59, and 7.74 sec.

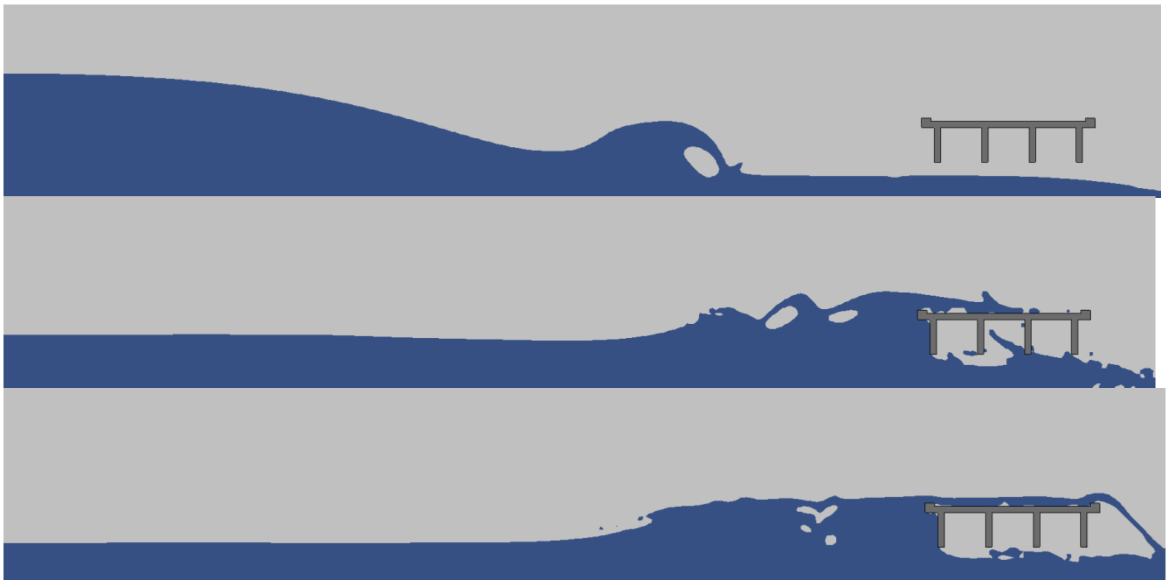

FIGURE 5: SCREENSHOTS OF FSI ANALYSIS AT 1.8, 5.59 AND 7.74 SEC FOR MODEL 2, FROM LS-PREPOST

For both Models 1 and 2, the influence of four combinations of flexibility was studied, as summarized in Table 2.

TABLE 2. FOUR CASES OF VARYING FLEXIBILITY

		Connection Type	
		Pins (Rigid)	Springs (Flexible)
Superstructure Type	Rigid	RP	RS
	Flexible	FP	FS

Figure 6 compares the applied tsunami load with the sum of the connection forcesand shows the effect of the flexibility on these forces, for wave type 1. For all cases, the horizontal and vertical (uplift) forces have been plotted.The external tsunami load was calculated by integrating the pressures acting on the bridge, while the connection forces are calculated from the dynamic equilibrium in the FSI analyses. It can be interestingly seen that the total connection forces in many cases are much larger than the applied load and this is due to the dynamic response of the bridge.This means that the practice of obtaining the maximum external wave load from a pure CFD analysis and applying it statically on a bridge model for finding the connection forces, might yield unconservative results. In addition, it may be observed from Figure 6 that the external applied tsunami load is different in the three different cases (RP, FP, FS) indicating the dependence of the wave load on the dynamic characteristics of the bridge. This observation suggests that the calculation of the wave load from a CFD analysis might not be sufficient and that dynamic FSI analyses might be required for accurate prediction of the wave load. Because LS-DYNA does not calculate connection forces directly for the rigid- pinned case, these are not included in the plots below.

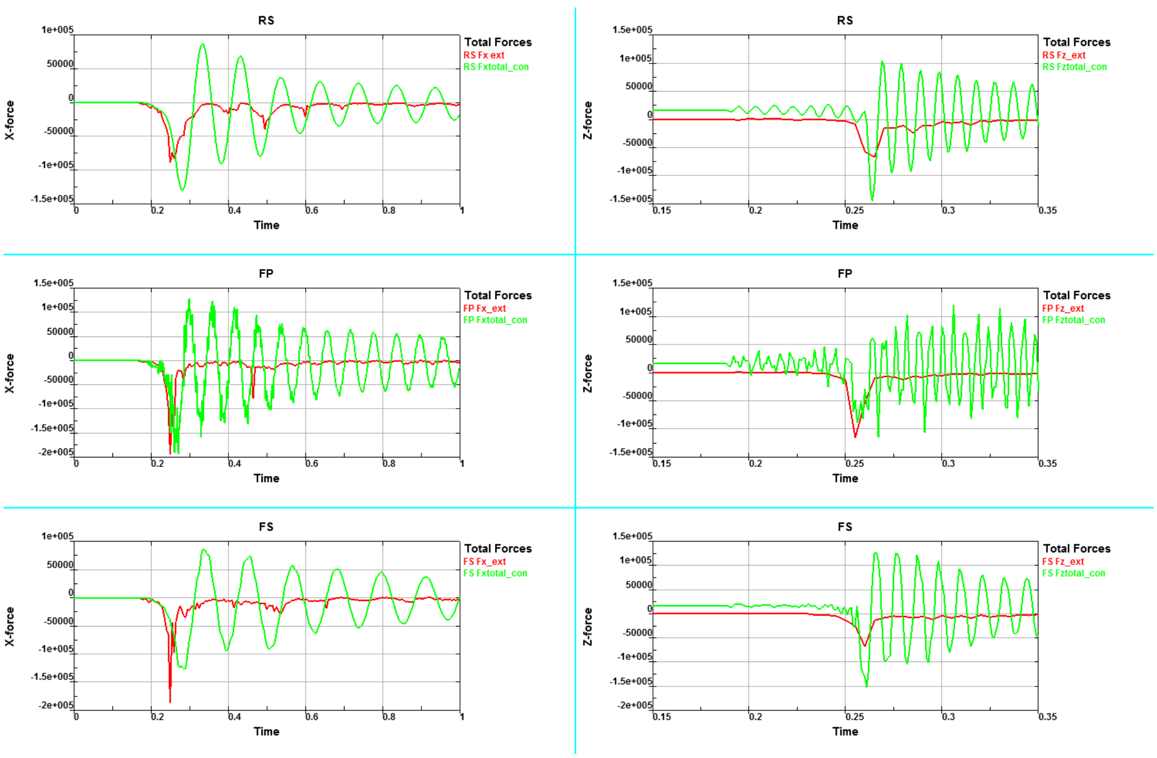

FIGURE 6: EFFECT OF FLEXIBILITY ON EXTERNAL LOAD AND TOTAL CONNECTION FORCES FOR MODEL 1

The distribution of tsunami forces in the connections for the three flexibility cases (RS,FP,FS) is shown in Figure 7. It is clearly seen that the flexibility significantly affects how much force is taken by each connection. For all the cases examined here, at the time of impact the offshore and onshore bearings are under tension and compression respectively, while the two bearings between them can be either in tension or in compression depending on the wave type and the flexibility case. In particular, the first bearing always takes the largest load, which can be several times larger than the load taken by the other bearings, depending again on the flexibility. In addition, it can be inferred from the pattern of forces in the connections, that there is significant rotation of the superstructure, which justifies the larger vertical forces in the offshore and onshore bearings.

Tables 3 and 4 show the maximum tsunami forces obtained in the above analyses for wave types 1 and 2 respectively. The external vertical load refers to uplift. The maximum connection force refers to the tensile force in the offshore bearing after the subtraction of the weight component. Since the equivalent 2D bridge slice consisted of 3D solids, there are two bearings for each girder, one on each side. Therefore, in order to calculate the total force taken by the two bearings under the offshore girder, the connection forces given in Table 3 and 4 should be multiplied by two. If this is done, then it can be observed that the total tensile force taken by the bearings under the offshore girder can be even higher than the total applied uplift force. This observation can be explained by the fact that for the two wave types were used in the analyses, the horizontal forces were much larger than the uplift forces, and they induced rotation of the deck that caused tension of the offshore bearings.

From tables 3 and 4 can be seen that the effect of the bearing and deck flexibility is not the same for the horizontal and vertical forces. In addition the effect of flexibility seems to change for the different wave types and this is probably due to the fact that different wave types excite different modes of the structure. However, in most cases the bearing flexibility seems to reduce the tsunami loads while the deck flexibility generally seems to increase the loads. Last but not least, comparison of the results in tables 3 and 4 shows the tsunami forces in model 1 are much larger than those in model 2. Inspection of the models and the fringe plots revealed that in the case of model 1, although an initial velocity of 7m/s was assigned, LS-DYNA accelerated the flow so that the wave impacted the bridge with a velocity three to four times higher. This is a numerical issue in LS-DYNA that has also been observed by Yim et al (2011), and which can probably be explained by the transient application of the gravity load.

The previous observations are very significant and could probably explain why so many bearings and connections failed in Japan during the Tohoku Tsunami in 2011. However, it must be pointed out that in this paper the role of FSI on tsunami forces on bridges was studied based on simplified 2D bridge models that do not capture accurately the dynamic behavior of a full 3D bridge model, but which are expected to behave in a similar way with the bridge cross-section at the middle of the span where no diaphragm exists. Therefore, these results must be verified with 3D FSI analyses that will more accurately capture the dynamic behavior of the bridge. In addition, more realistic waves should be used in order to be sure the tsunami waves are simulated accurately. However, due to the complexity of the FSI analyses, these numerical results should also be validated against other numerical software tools and ideally with an FSI experiment. For the time being, the significance of the flexibility has been identified experimentally by Higgins *et al* (2013) for the case of storm surge loads on bridges, which indicates that the numerical analyses are in the right direction.

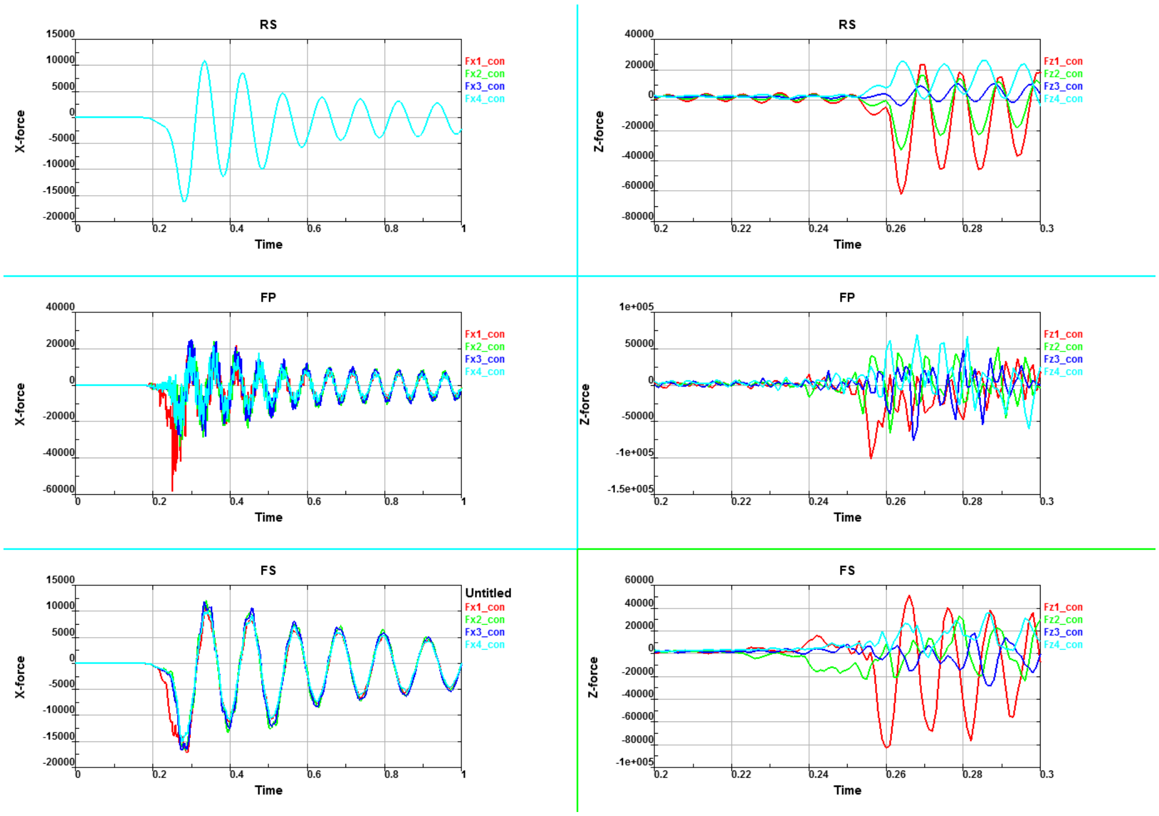

FIGURE7: EFFECT OF FLEXIBILITY ON THE DISTRIBUTION OF THE TSUNAMI LOAD AMONG THE CONNECTIONS FOR MODEL 1

Conclusions:

Advanced fluid-structure interaction analyses were conducted using the ALE method in LS-DYNA. In the 2D numerical model the flexibility of the superstructure and the connections was modeled and their role was studied. Both the superstructure and substructure flexibility seemed to significantly influence the external loads induced by the tsunami. In particular, it was seen that both the applied tsunami load (calculated from integration of pressures) and the connection forces were strongly influenced by flexibility. This is probably due to the fact that the flexibility affects the dynamic characteristics of the bridges and consequently the dynamic interaction with the tsunami waves. Another significant observation is that in most of the above cases the total forces in the connections were larger than the applied tsunami load which indicated again that structural dynamics and inertia forces play a major role. Moreover, the distribution of forces between the connections was also affected by the flexibility which indicates that FSI analyses might be a necessary tool for the design of tsunami resilient bridges. Last but not least, it was observed that the total tensile force in the bearings under the offshore girder can be even higher than the total applied uplift force. Since the field of FSI is still in its early stage there is a strong need for validation of numerical results against experimental data.

TABLE 3. MAXIMUM TSUNAMI FORCES FOR MODEL 1

Forces	**Rigid & Pins (RP)** (kN)	**Rigid & Springs (RS)** (kN)	**Flexible & Pins (FP)** (kN)	**Flexible & Springs (FS)** (kN)
Max External Load				
Horizontal	108	88.6	194	187
Vertical	105	67	115	68
Max Sum of Reactions				
Horizontal	NA	130	194.6	126
Vertical	NA	160.8	136	167.6
Max Con. Force				
Horizontal	NA	16.2	58.5	17.2
Vertical	NA	62	101.3	83.3
Ratios ofMax Sum of Reactions/Max External Load				
	Rigid & Pins	Rigid & Springs	Flexible & Pins	Flexible & Springs
Horizontal	NA	1.47	1.00	0.67
Vertical	NA	2.4	1.18	2.46

	Role of Bearing Flexibility		**Role of Deck Flexibility**	
Ratios	RS/RP	FS/FP	FP/RP	FS/RS
Max External Load				
Horizontal	0.82	0.96	1.8	2.11
Vertical	0.64	0.59	1.10	1.01
Max Sum of Reactions				
Horizontal		0.65		0.97
Vertical		1.23		1.04
Max Con. Force				
Horizontal		0.29		1.06
Vertical		0.82		1.34

TABLE 4.MAXIMUM TSUNAMI FORCES FOR MODEL 2

Forces	**Rigid & Pins** (KN)	**Rigid&Springs** (KN)	**Flexible & Pins** (KN)	**Flexible&Springs**(KN)
Max External Load				
Horizontal	22.5	26.6	27.4	23.6
Vertical	6.90	5.60	5.3	4.5
Max Sum of Reactions				
Horizontal	NA	23.5	29.8	32.2
Vertical	NA	6.10	16.5	11.1
Max Con. Force				
Horizontal	NA	2.9	7.2	4.8
Vertical	NA	4.00	7.7	6.4
Ratios ofMax Sum of Reactions/Max External Load				
	RP	**RS**	**FP**	**FS**
Horizontal	NA	0.88	1.10	1.36
Vertical	NA	1.09	3.11	2.47

	Role of Bearing Flexibility		**Role of Deck Flexibility**	
Ratios	RS/RP	FS/FP	FP/RP	FS/RS
Max External Load				
Horizontal	1.18	0.86	1.22	0.89
Vertical	0.81	0.85	0.77	0.80
Max Sum of Reactions				
Horizontal		1.08		1.37
Vertical		0.67		1.82
Max Con. Force				
Horizontal		0.68		1.66
Vertical		0.83		1.60

References

Bricker J.D., Kawashima K. and Nakayama A. (2012). "CFD analysis of bridge deck failure due to tsunami." Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, Tokyo, Japan

Bungartz, H. J., & Schäfer, M. (Eds.) (2006). "Fluid-structure interaction: modelling, simulation, optimisation (Vol. 1)." Springer Science & Business Media.

CD-adapco (2013) : STAR-CCM+ v8.06.005 Manual

Fu L., Kosa K. and Sasaki T. (2013). “Tsunami damage evaluation of Utatsu Bridge by Video and 2-D simulation analyses”. Journal of Structural Engineering Vol.59

Hallquist, J.O (2014). LS-DYNA Theoretical Manual, Livermore Software Technology Corporation, Livermore, CA

Hayashi H. (2013). “Study on tsunami wave force acting on a bridge superstructure.” Proc. of 29th US-Japan Bridge Engineering Workshop, Tsukuba, Japan

Hayatdavoodi, M., Seiffert, B. and Ertekin, R. C. (2014). “Experiments and computations of solitary-wave forces on a coastal-bridge deck. Part II: Deck with girders.” Coastal Engineering, 88, 210-228.

Higgins, C., Lehrman J, Bradner C., Schumacher T., and Cox D. (2013). “Hybrid testing of a prestressed girder bridge to resist wave forces” Proc. of 29th US-Japan Bridge Engineering Workshop, Tsukuba, Japan

Hoshikuma J., Zhang G., Nakao H. and Sumimura T. (2013). “Tsunami-induced effects on girder bridges.” Proceedings of the International Symposium for Bridge Earthquake Engineering in Honor of Retirement of Professor Kazuhiko Kawashima, Tokyo, Japan,

Kataoka S. and Kaneko M. (2013): “Estimation of Wave Force Acting on Bridge Superstructures due to the 2011 Tohoku Tsunami” Journal of Disaster Research Vol. 8

Kosa K., Nii S., Miyahara K., and Shoji M. (2012). “Experimental study for estimating tsunami forces acting on bridge girders.” Proc. of 26th US-Japan Bridge Engineering Workshop, Louisiana, United States

Lau, T. L., Ohmachi, T., Inoue, S. and Lukkunaprasit, P. (2011). “ Experimental and Numerical Modeling of Tsunami Force on Bridge Decks.” DOI: 10.5772/23622.

LS-DYNA Aerospace Working Group (AWG) (2013). Modeling Guidelines Document. http://awg.lstc.com/tiki/tiki-index.php?page=MGD

Martinelli L., Lamberti A., Gaeta M. G., Tirindelli M., Alderson J., Schimmels S. (2010). “Wave Loads on Exposed Jetties: Description of Large-Scale Experiments and Preliminary Results.” Proceedings of the International Conference on Coastal Engineering; No 32

Maruyama K. , Tanaka Y., Kosa K. , Hosoda A., Mizutani N., Nakamura T.(2013). “Evaluation of tsunami force acted on bridges by Great East Japan Earthquake.” 10 CUEE Conference Proceedings, Tokyo, Japan

Murakami, K., Sakamoto, Y. and Nonaka, T. (2012). “Analytical investigation of slab bridge damages caused by tsunami flow.” Coastal Engineering Proceedings, *1*(33), structures-42.

Seiffert, B., Hayatdavoodi, M. and Ertekin, R. C. (2014). “Experiments and computations of solitary-wave forces on a coastal-bridge deck. Part I: flat plate.” Coastal Engineering, 88, 194-209

Souli M., Olovsson L, Do I. (2009). “ALE and Fluid-Structure Interaction Capabilities in LS-DYNA.” 7th International LS-DYNA Users Conference

Yim, S. C., Boon-intra, S., Nimmala, S. B., Winston, H. M.,Azadbakht, M., & Cheung, K. F. (2011). “Development of a Guideline for Estimating Tsunami Forces on Bridge Superstructures ” Oregon Department of Transportation Report No. OR-RD-12-03