Effect of the Seismic wave Direction on the Collapse of RC Box Girder Bridges

M. M. Husain[a], Heba A. Mohamed[a], Ayman Aboraia[b]
[a]Structural Engineering Dept., Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt.
[b]Construction and Building Dept., High Institute of Engineering, October 6th city, Giza. 12592, Egypt.

***Abstract*:- The gradual collapse of ordinary structures due to gravity and blast loads is the subject of a significant number of research studies. The progressive collapse caused by seismic actions, especially of bridge structures, is being investigated by a few others. Some of the serious earthquakes in the past have resulted in significant damage or the collapse of bridge buildings, resulting in devastating losses. New analysis and monitoring methods for the damage process, from initial failure to final collapse and can follow the structural failure trend, have been built in order to construct new improved earthquake-resistant bridges. The current paper analyzes the behavior of bridge progressive collapse by serious seismic actions using the Applied Element Approach [AEM], which takes into account the separation of structural members or components, from failure to complete collapse, and falling contact debris or impact forces. A monolithic RC box girder bridge were numerically analyzed under the influence of Kobe seismic ground motion in longitudinal and transverse directions. The results showed that the effect of the seismic wave in the longitudinal direction of the bridge was more destructive than that in the transverse direction.**

Keywords:- Progressive collapse; applied element method; box girder; Ground motion direction

1. INTRODUCTION

Progressive collapse phenomenon is defined as the global damage or collapse behavior of a large part of the structural system that is caused by a failure of a relatively small or localized part of the structure. Structural Progressive collapse occurs as a result of failure of one or more structural members or components. The load is transferred in the structural system due to changes in the distribution of stiffness, the pattern of the stress behavior, and/or the structural boundary conditions (Krauthammer et al., 2002). This initial failure results in other structural elements being further overloaded and later fail. Studies on the progressive collapse of existing structures have focused primarily on high impact as in blasting or irregular loading. Not so much attention is paid to the vulnerability of structures, especially bridges, with regard to progressive collapse during earthquakes (Starossek U., 2006).

Wibowo et al., (2009) studied the seismic progressive collapse of RC bridges during earthquakes. They modeled only a continuous bridge that was previously experimented with "Guedes, 1997”. The results have shown a good agreement. The separation of structural components resulting from fracture failure and impact forces from falling debris had been taken into consideration. The results have shown a significant influence on the performance of bridges during major earthquakes that were visible in its progressive collapse analysis. These also demonstrate the need to include progressive failure mechanisms in the assessment of seismic design efficiency and bridge evaluation that would not only lead to a better and more robust earthquake-resistant design for new structures but also more efficient retrofitting and reinforcement strategies for older structures.

In a similar vein, Salem et al., (2016) analyzed numerically the collapse of Tsuyagawa Bridge damaged by the Tohoku Tsunami in March 2011. The Tohoku Tsunami swept across Japan's eastern coast killing over 15,000 people and missing over 2,500. The tsunami caused more than 400,000 buildings to collapse and more than 250 coastal bridges to be washed away. The analysis showed accurately the collapse behavior of the bridge, showing that the bridge collapsed at a water velocity of 6.6 m/s caused by its piers' flexural failure. Tsuyagawa Bridge's AEM analysis has shown the ability to simulate the 2011 Tohoku Tsunami collapse effectively, although the analytical results showed less ductility when compared to reality.

Domaneschi et al., (2020) analyzed numerically the collapse of the viaduct over the Polcevera Valley in Genoa that collapsed in August 2018. This incident left 43 deaths, and several injuries caused by a collapse of a portion of the highway connection. The results of the analysis showed that the stay cable was the most important item whose failure caused the collapse. Furthermore, the simulation model indicated that the main girder triggered the collapse and the large visible displacements involved in their collapse would have warned the authorities of the impending fault.

2. APPLIED ELEMENT METHOD

The Extreme Loading for Structures (ELS) program, developed by ASI-2018 is based on the AEM, which was initially developed by Tagel-Din and Meguro (2000a, b) at the University of Tokyo in 1998 to solve problems related to two-dimensional plane stresses. It was later expanded to solve three-dimensional problems. The AEM is a novel method of modeling that adopts the discrete cracking concept in AEM. Structures are modeled as an element assembly. The elements are not rigid and connected by normal and shear springs along their joint surfaces. These springs are responsible for normal and shear stresses transfer between adjacent elements. Each spring represents a certain volume of material stresses and deformations. Once the connecting springs

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 12, December-2020

fail, each of the two adjacent elements can be completely separated. The AEM adopts fully nonlinear path-dependent material constitutive models. AEM is a stiffness-based approach in which an overall stiffness matrix is formulated and equilibrium equations for each of the stiffness, mass and damping matrices for structural deformations (displacements and rotations) are nonlinearly solved. The equilibrium equation solution is an implicit one that takes step-by-step dynamic integration (Newmark-beta time integration procedure) (Bathe 1995; Chopra 1995). If the springs connecting the elements are ruptured, two adjacent elements are separated from each other. Elements may separate, recontact, or contact other elements automatically depending on the structural response.

3. MATERIAL MODELS

3.1 Modeling concrete and reinforcing steel

Maekawa model is used to model concrete in compression, whereas for concrete in tension, the linear stress-strain relationship is adopted. In this stage, concrete is exposed to tension up to cracking where the stresses are set to zero afterward. Furthermore, for concrete in shear, a linear relationship between shear stresses and strain is assumed before the cracking. After cracking, a drop in the value of shear stresses to zero takes place (H. Okamura and M. Kohichi, 1991). Springs are also used to define the reinforcement between elements. Ristic model, Ristic, D., (1986) is used to model the reinforcement. Newmark-β approach is used to solve equations of dynamics. The Equilibrium equations are indeed linear for each step and are generally solved, in AEM, by using a direct or an iterative solver.

3.2 Bridge bearing material

An interface material is used to model bearings. The interface material model is a pre-cracked element where the material is initially cracked and cannot bear tensile stresses. As for compression, the stress-strain relation is linear up to compression failure stress. The relationship between shear stress and shear strain is linear until the shear stress approaches $\mu\sigma n$ (coefficient of normal friction x normal stress). At this stress level, the shear stress remains the value ($\mu\sigma n$) as long as there is no change in normal stresses. The compressive stress variation allows the proportional variation in shear stresses ($\mu\sigma n$). The shear stiffness is set as a minimum, if the crack opens or during active sliding of the bearing. (Salem et al., 2016)

4. COMPARISON OF AEM AND FEM.

During progressive collapse analysis, the failure, separation, contact, and falling debris of elements must be traced. Using FEM, It is very difficult to model progressive collapse. On the other hand, using AEM, to analyze these processes is made easy and effective taking into consideration all the analysis stages until collision, Fig. 1.

	Small Displacement		Large Displacement			Collision
	Elastic	Cracking, Yield, Crushing	Buckling, Post-Bulking	Element Separation	Debris falling as rigid bodies	Progressive Collapse
	Linear	Nonlinear				
AEM	Accurate	Reliable Results				
FEM	Accurate	Reliable Results		Not Automated		Time Consuming

Figure 1. Scope of FEM and AEM.

6. BRIDGE MODELS

6.1. Bridge layout

RC box girder bridge were modeled 3 spans with 25m span, Fig. 2. The bridge superstructure is monolithic box girder with columns. The columns are assumed to be fixed at its bases. The bridge box girder is rested on five elastomeric bearings plates at the superstructure edges. The bridge dimensions and reinforcement details were originally taken from executed multi-span box girder bridges in Egypt. The reinforced concrete damping ratio is assumed 5% during the analysis. The analyzed bridge model and the reinforcement of the box girder is shown in Fig.3, and Table 1. The purpose of analyzing models A1-K-L and A1-K-T is to determine the effect of severe seismic ground motions, like Kobe, on RC box girder when applied on longitudinal and transverse direction.

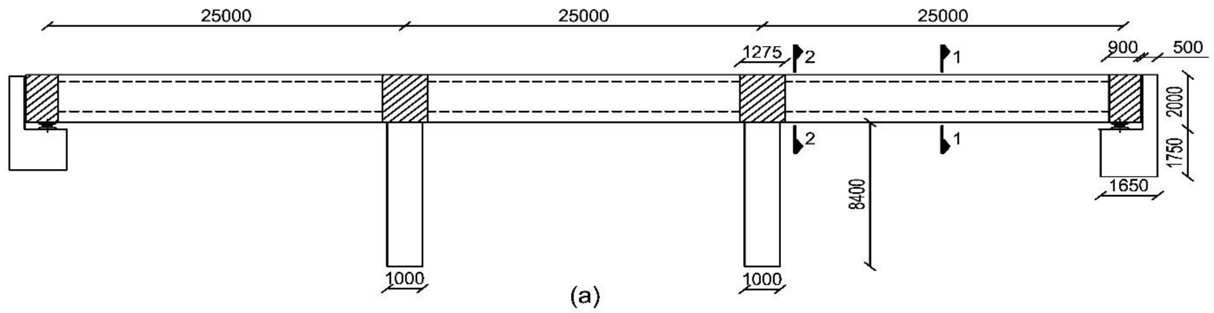


Figure 2. Layout of the box girder bridges: (a) monolithic with columns; (b) continuous on bearing; (c) simple box girder bridges on bearing.

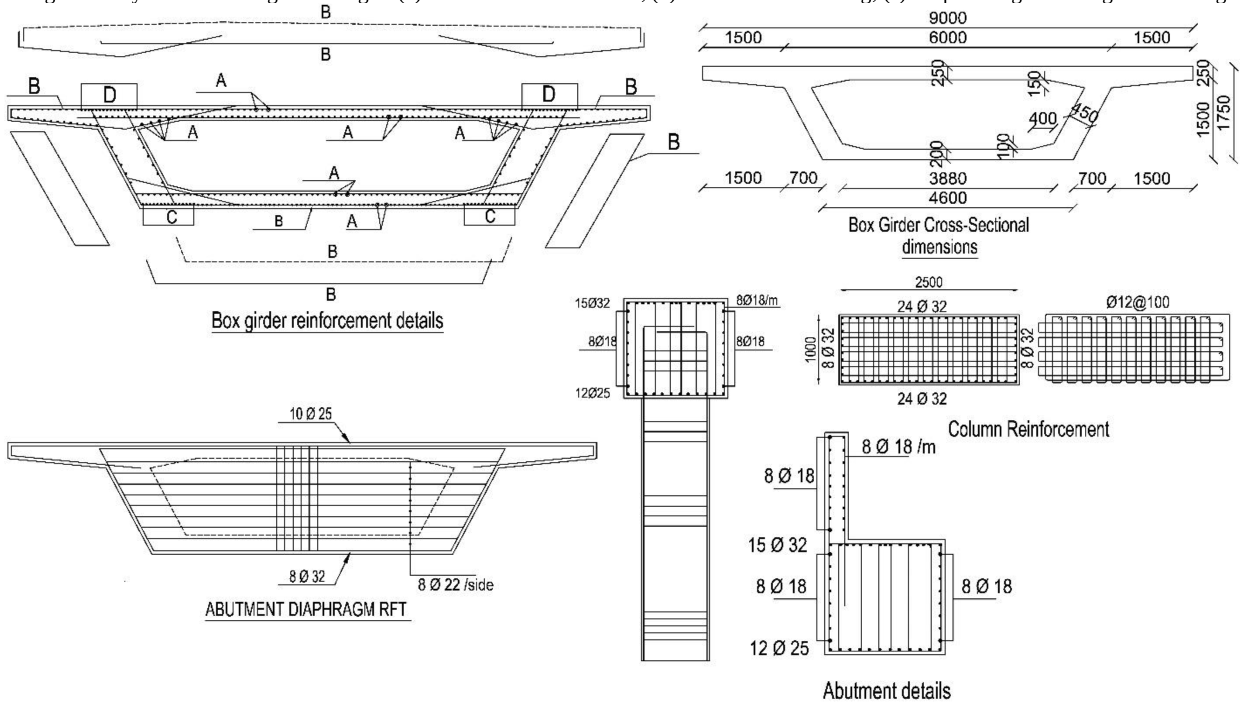


Figure 3. Dimensions of the box girder and reinforcement details of the bridge elements.

Table 1: Bridge models and box girder reinforcements (unit: mm).

Model*	Ground Motion	Bridge System	Sec.	Reinforcement of the box girder			
				A	B	C	D
A1-M-L	Kobe	Monolithic	1	Ø10/125	Ø10/125	30Ø16	10Ø16
			2				
A1-M-T			1				
			2				

6.2 Material properties

The material properties adopted in AEM analysis are presented in Table 2. A full bond between the concrete and the reinforcing steel was assumed. The used bearing was composed of a top and bottom steel plates and bearing material in between as in Salem et al., (2016). The dimensions of the steel plates used were 500x500x50 mm. The dimension of the elastomeric bearing interface was assumed 350x350x130 mm, Akogul, C. and Celik, O., (2008). The interface between the steel plates was given bearing material properties, Salem et al., (2016). A relatively high compressive strength was given to the bearing interface so it could not fail in compression and act linearly (Chen, W. F., and Duan, L., 2014). The shear modulus of the bearing was assumed to be 2Mpa (Malek S., 2007 , and Can Akogul and Oguz C., 2008).

Table 3: Properties of the bridge materials.

Parameter	Concrete	Steel Reinforcement & plates	Bearing interface	unit
Compressive Strength	4e06	3.6e07	5.51e+07	kg/m²
Tensile Strength	4e05	3.6e07	--	kg/m²
Young's Modulus	2.213e09	2.0389e+09	2.0389e+09	kgm²
Shear Modulus	984297e03	8.1556e+09	203943	kg/m²
Specific Weight	2500	7840	7840	kg/m³

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 12, December-2020

Separation Strain	0.2	0.12	1	---
Friction Coefficient	0.8	0.8	0.6	---
Ultimate Strength / Tensile Stress	--	1.4444	--	---
Normal Contact Stiffness Factor	0.0001	0.0001	0.0001	---
Shear Contact Stiffness Factor	1.00e-05	1.00e-05	1.00e-05	---
Contact Spring Unloading Stiffness Factor	2	2	2	---
Post Yield Stiffness Ratio	--	0.01	--	---

7. GROUND ACCELERATION

Kobe, ground acceleration was used in the collapse analysis of the bridge models, as there was some bridge collapse during these earthquakes, Mitchell et al., (1995), Anderson et al., (1996), Kawashima, (2000), Wallace, et al., (2001), and Hsu and Fu, (2004). The ground motions data was obtained from the Pacific Earthquake Engineering Research (PEER), Strong Motion Database (PEER, 2019). A summary of the earthquake ground motions used in this research is presented in Table 3 and is shown in Fig. 4. The time used in the seismic analysis was reduced to the time that contains the largest cycles of seismic accelerations to reduce the ELS analysis time, as the time that would not contain significant values of acceleration could be omitted. The used time step during the analysis was 0.004. Earthquake analysis usually requires ΔT of 0.001-0.01 sec. when a collision is expected to occur. The smaller the time step the higher the accuracy and the convergence of results becomes.

Table 3: Seismic ground motions.

Earthquake	Year of Occurrence	Record Station	PGA in X-Dir.	Moment Magnitude	Original Duration	Reduced Duration
Kobe	**Jan 1995**	**KJMA**	**0.834g**	**6.9**	**90**	**20**

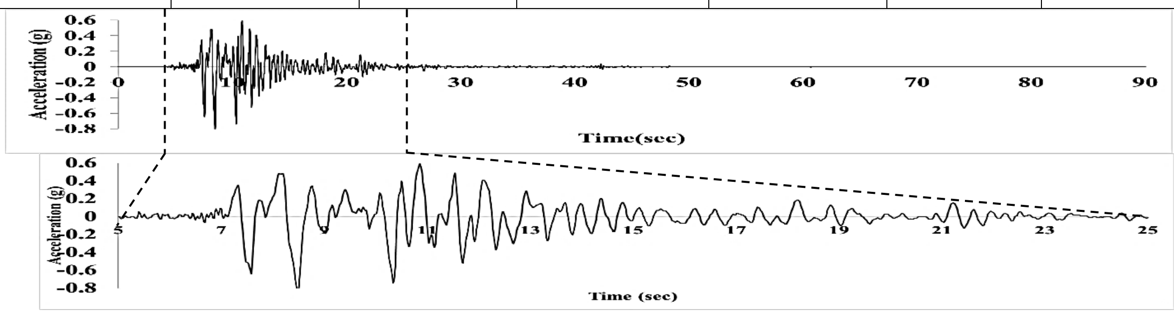
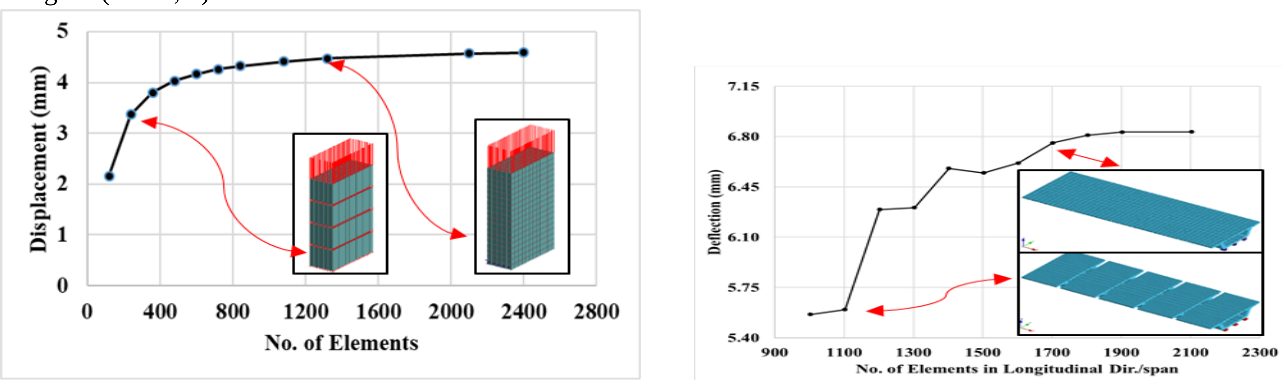


Figure 4. Original and reduced 1995, Kobe earthquake ground motion.

8. MESH SENSITIVITY ANALYSIS

A mesh sensitivity analysis was carried out to obtain a suitable mesh size that would be used in all the analysis cases for columns and bridge superstructure. Horizontal and vertical concentrated loads were used for the column and the box girder respectively. Fig. 5 shows the relationship between the mesh elements and the displacement of the column and the deflection of the box girder. 22 elements per column`s height and 5x12 elements per columns` cross-section were used. The maximum dimensions for the columns` elements were 200x200 mm per element cross-section and was 38 cm per element height. Each surface area of the box girder (i.e., the deck, soffit, and webs) was divided into 5x1 elements with 50 elements per 25 m length (span) in the box girders` longitudinal direction. This mesh size was found to give accurate results. An analysis using a finer mesh has been carried out without any noticeable difference in the displacement and deformation. The total number of elements used was 10,000,. The AEM mesh used was accurate enough during the elastic region and in the small deformation range of the inelastic region, Tagel-Din and Meguro (2000a, b).



International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 12, December-2020

(a) Column (b) Box Girder

Figure 5. Mesh sensitivity of the column, and the box girder.

9. ANALYSIS RESULTS

The analysis was carried out on two stages; the first was static to take into account the gravity loads and original deformations of the bridge, whereas the second was a dynamic analysis.

9.1. Reinforcement reduction effect

Fig. 6 shows the displacement time history for the right column of A1-M-L, A1-M-T, and models. The two models showed a relatively identical displacement pattern until the 16th second, as the displacement of model A1-M-L increased due to the total collapse of the right and middle box girders. It is noted that model A1-M-L showed greater by double displacement than of model A1-M-T. The reason that the rigidity of the column in the longitudinal direction is lower than that in the transverse direction

Fig. 7 shows the straining actions. The straining actions of A1-M-L, A1-M-T. at the 8th second, the axial force of model A1-M-L is reduced by 50% as the right bay of the box girder collapsed. At the 21th second, after the collapse of the middle bay of the box the axial force is nearly zero. At the 14th second, the axial force of model A1-M-T is reduced after the failure of the right bay of the box girder.it is also noted that the right column of model A1-M-T exhibited greater moment than model A1-M-L.

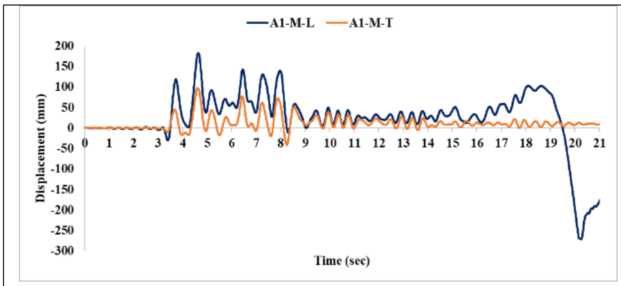


Figure 6. Displacements-time history of the right column of models "A1-M-L, and A1-M-T,"

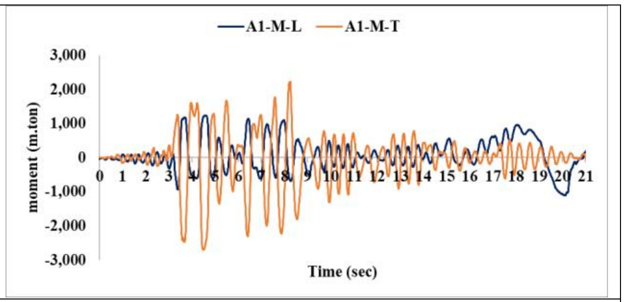


Figure 7.b. Moment-time history of the right column of models "A1-M-L, and A1-M-T,"

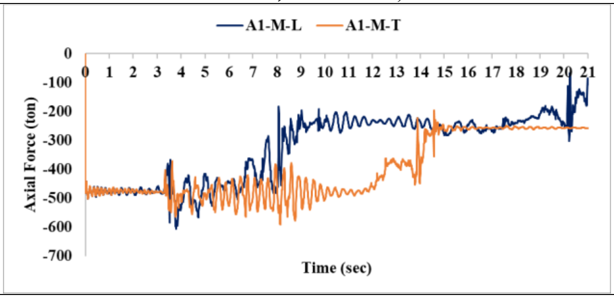


Figure.7.a. Axial force-time history of the right column of models "A1-M-L, and A1-M-T,"

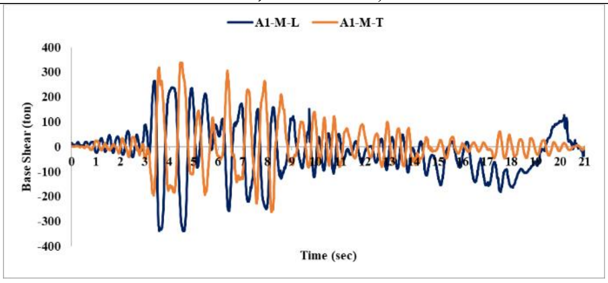


Figure 7.c. Base shear-time history of the right column of models "A1-M-L, and A1-M-T,"

9.3. Collapse analysis of the different bridge models during Kobe ground motion

A comparison between models A1-M-L, A2-M-T, are presented in Figs. 11, 12, respectively. At the end of the analysis time, A1-M-L and A2-M-T collapsed. Reinforcement reduction beyond the minimum reinforcement ratio, model A3-M-K according to the ECP203-2007, allowed the bridge model to show a collapse behavior. At failure initiation after 4 seconds, the webs of the box girder showed excessive cracks. At 7.25 seconds, the web of the right box girder failed mainly in shear. At 8 seconds, the right bay of the box girder hit the ground. At the 15th second, the left box girder initiated failure in shear and settled on the ground. At analysis termination reaching the 20th second, the middle bay failed and the bay weight dragged the left column down. Contrary to expected , by changing the ground motion direction from longitudinal to transverse direction, model A1-M-T showed a less collapse pattern as the right bay of the box girder is the only collapsed part of the bridge model.

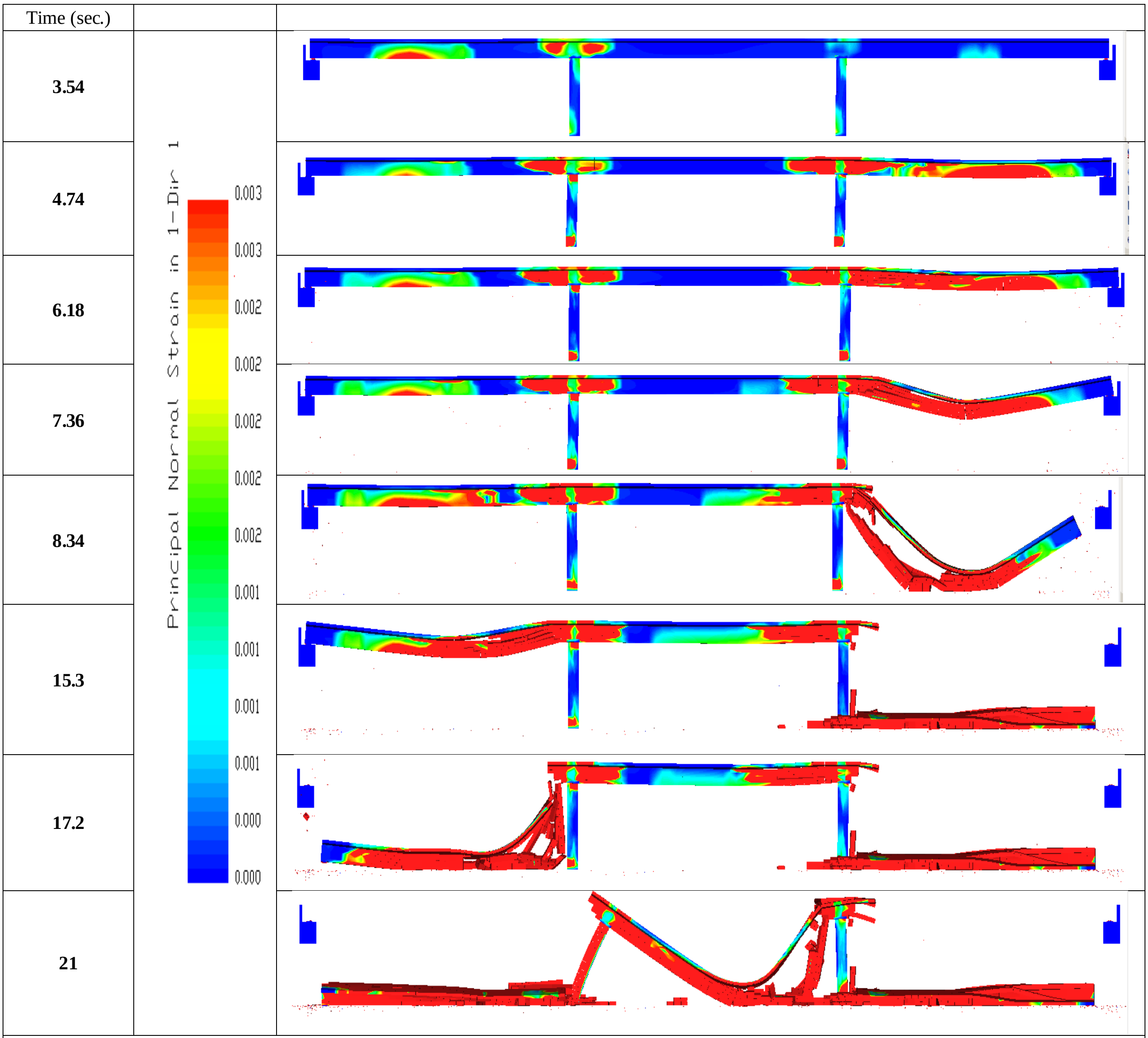


Figure 8.a. 2D-view of the principal normal strain during the time history “Model A1-L-K”.

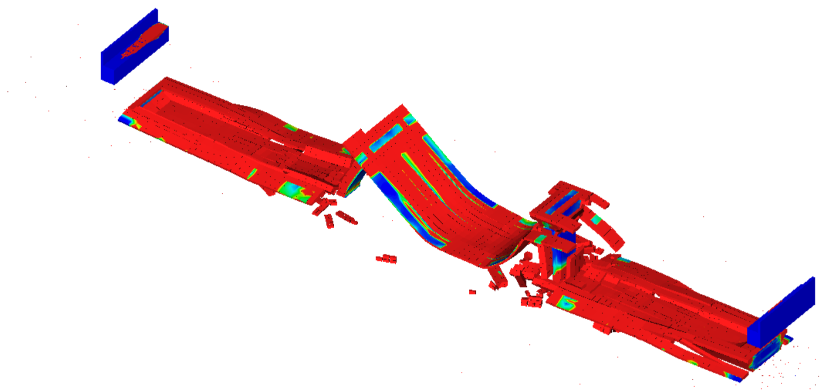


Figure 8.b. 3D-view of the principal normal strain during the time history “Model A1-L-K.”

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 12, December-2020

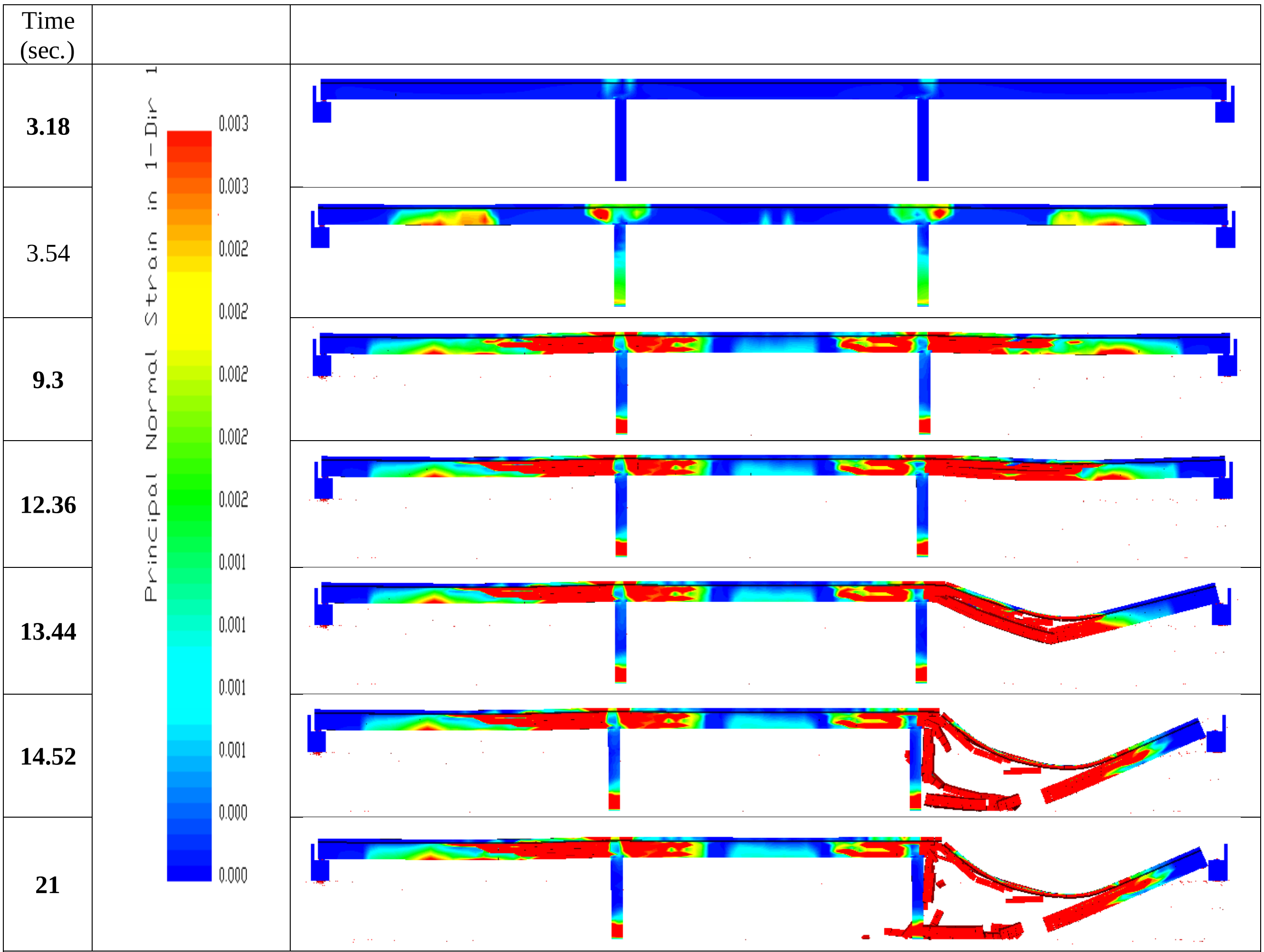


Figure 9.a. 2D-view of the principal normal strain during the time history “Model A1-T-K”.

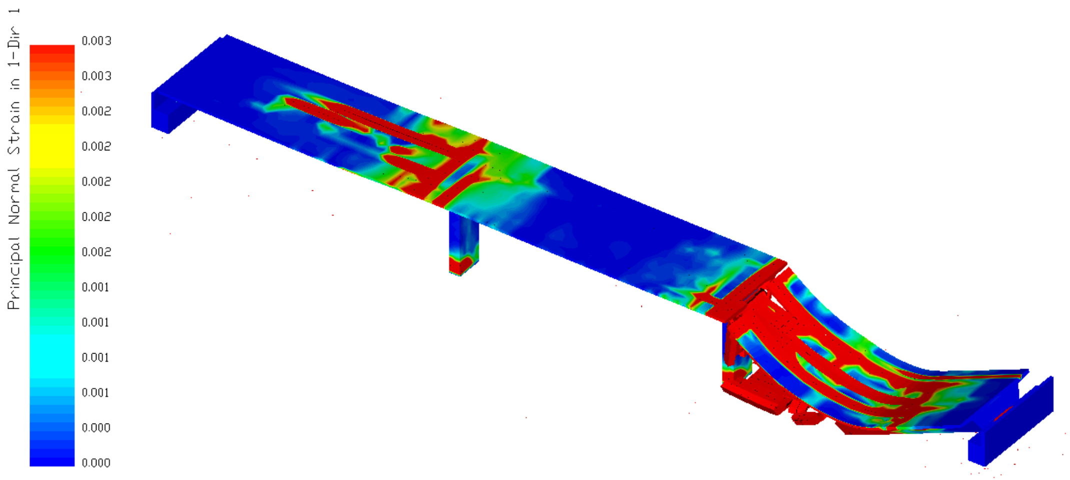


Figure 9.b. 3D-view of the principal normal strain during the time history “Model A1-T-K”.

10. CONCLUSION

In the current study, the seismic progressive collapse behavior and analysis of reinforced concrete bridges were analyzed. Various bridge configurations: monolithic with columns, continuous on bearings, simple on bearings bridge models were analyzed. The bridge models and selected earthquake excitations used in the study were discussed. A summary of the findings is presented herein.

- ELS program can be a means to predict the behavior of ordinary and special structures against abnormal events during the design, construction, and service loads.
- Bridges can be analyzed with respect to the direction of the ground motion, obtaining the collapse pattern, and analyzing the necessary strengthening to prevent the possibility of collapse using ELS program.
- Contrary to expected, the effect of the seismic ground motions in longitudinal direction is more destructive than its effect in the transverse direction.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets used to defend the findings of this study are incorporated into the article.

FUNDING STATEMENT

No funding

REFERENCES

[1] Akogul, C., and Celik, O. (2008). Effect of Elastomeric Bearing Modeling Parameters on The Seismic Design of RC Highway Bridges With Precast Concrete Girders.
[2] Anderson, D. L., Mitchell, D., and Tinawi, R. G. (1996). Performance of Concrete Bridges during the Hyogo-ken Nanbu (Kobe) Earthquake on January 17, 1995. Canadian Journal of Civil Engineering, 23 (3), pp. 714-726.
[3] Aria, M., & Akbari, R. (2013). Inspection, Condition Evaluation, and Replacement of Elastomeric Bearings in Road Bridges. Structure and Infrastructure Engineering, 9(9), 918–934.
[4] ASI (Applied Science International). (2018). Extreme loading for structures 3.1. ⟨http://www.appliedscienceint.com/extreme-loading-forstructures/⟩ (May 10, 2018).
[5] Bathe, K. (1995). Solution of equilibrium equations in dynamic analysis, Prentice Hall, Englewoods Cliffs, NJ.
[6] Can Akogul, & Oguz C. Celik. (2008). Effect of Elastomeric Bearing Modeling Parameters on The Seismic Design of Rc Highway Bridges With Precast Concrete Girders. The 14th World Conference on Earthquake Engineering. October 12-17, 2008, Beijing, China
[7] Chiara, C., & Rui, P. (2006). Seismic response of continuous span bridges through fiber-based finite element analysis. Earthquake Engineering and Engineering Vibration, 5(1), 119–*131*. DOI:10.1007/s11803-006-0631-0
[8] Chen, W.-F., & Duan, L. (2014). Bridge engineering handbook. Boca Raton: CRC Press, Taylor & Francis Group.
[9] Chopra, A. (1995). Dynamics of structures: Theory and applications to earthquake engineering, Prentice-Hall, Englewood Cliffs, NJ.
[10] Corley, W. G. (2002). Applicability of Seismic Design in Mitigating Progressive Collapse. In National Workshop on Prevention of Progressive Collapse, Rosemont, IL, July 10-11. Multi-hazard Mitigation Council of the National Institute of Building Sciences, Washington, DC, U.S.A., 13 pp.
[11] Domaneschi, M., Pellecchia, C., De Iuliis, E., Cimellaro, G. P., Morgese, M., Khalil, A. A., & Ansari, F. (2020). Collapse analysis of the Polcevera viaduct by the applied element method. Engineering Structures, 214, 110659. DOI:10.1016/j.engstruct.2020.110659.
[12] ECP203-2007, Egyptian Code Design and Construction for Reinforced Concrete Structures. Research Centre for Houses Building and Physical Planning, Cairo, Egypt.
[13] Guedes, J. (1997). Seismic Behavior of Reinforced Concrete Bridges: Modelling, Numerical Analysis, and Experimental Assessment. Ph.D. Thesis, Department of Civil Engineering, University of Porto, Portugal.
[14] Gurley, C. (2008). Progressive Collapse and Earthquake Resistance. Practice Periodical on Structural Design and Construction ASCE, 13 (1), pp. 19-23.
[15] H. Okamura and M. Kohichi, "Nonlinear Analysis and Constitutive Models of Reinforced Concrete," Vol. 10, Gihodo, Tokyo, Japan, 1991.
[16] Hayes, J. R., Jr., Woodson, S. C, Pekelnicky, R. G., Poland, C. D., Corley, W. G., and Sozen, M. (2005). Can Strengthening for Earthquake Improve Blast and Progressive Collapse Resistance. Journal of Structural Engineering ASCE, 131 (8), pp. 1157-1177.
[17] Hsu, Y. T. and Fu, C. C. (2004). Seismic Effect on Highway Bridges in Chi-Chi Earthquake. Journal of Performance of Constructed Facilities ASCE, 18 (1), pp. 47-53.
[18] Krauthammer T., Robert L. Hall, Stanley C. W., James T. B., and John R. H. (2002). Development of Progressive Collapse Analysis Procedure and Condition Assessment for Structures. Protective Technology Center, The Pennsylvania University, Philadelphia, PA,19104.
[19] Kawashima, K. (2000). Seismic Performance of RC Bridge Piers in Japan: An Evaluation After the 1995 Hyogo-ken Nanbu Earthquake. Progress in Structural Engineering and Materials, 2(1), pp. 82-91.
[20] Lau, D. T., & Wibowo, H. (2010). Seismic Progressive Collapse Analysis of Reinforced Concrete Bridges by Applied Element Method. Earth and Space 2010. DOI:10.1061/41096(366)287
[21] Maekawa, K., and Okamura, H. (1983). The deformational behavior and constitutive equation of concrete using the elastoplastic and fracture model. J. Faculty Eng. Univ. Tokyo (B), 37(2), 253-328.
[22] Malek, S., (2007). ESTIMATION OF ELASTOMERIC BRIDGE BEARING SHEAR MODULUS USING OPERATIONAL MODAL ANALYSIS. semanticscholar.org, Corpus ID: 159035559.
[23] Mitchell, D., Bruneau, M., Williams, M., Anderson, D., Saatcioglu, M., and Sexsmith, R. (1995). Performance of Bridges in the 1994 Northridge Earthquake. Canadian Journal of Civil Engineering, 22 (2), pp. 415-427.
[24] PEER Ground Motion Database - PEER Center. [online] Available at:https://ngawest2.berkeley.edu/spectras/191246/searches/176626/edit [Accessed 17 Jan. 2019]. Ngawest2.berkeley.edu. (2020).
[25] Ristic D., "Stress-strain based modeling of hysteretic structures under earthquake-induced bending and varying axial loads," Research Report No. 86-ST-01, School of Civil Engineering, Kyoto University, Kyoto, Japan, 1986.
[26] Salem, H., Mohssen, S., Nishikiori, Y., & Hosoda, A. (2016). Numerical Collapse Analysis of Tsuyagawa Bridge Damaged by Tohoku Tsunami. Journal of Performance of Constructed Facilities, 30(6), 04016065. DOI:10.1061/(ASCE)cf.1943-5509.0000925.
[27] Seyedkhoei, A., Akbari, R., & Maalek, S. (2019). Earthquake-Induced Domino-Type Progressive Collapse in Regular, Semiregular, and Irregular Bridges. Shock and Vibration, 2019, 1–18. DOI:10.1155/2019/8348596

[28] Seible, F., Hegemier, G., Karbhari, V. M., Wolfson, J., Arnett, K., Conway, R., and Baum, J. D. (2008). Protection of Our Bridge Infrastructure against Manmade and Natural Hazards. Structure and Infrastructure Engineering, 4 (6), pp. 415-429.

[29] Starossek, U. (2006). Progressive Collapse of Structures: Nomenclature and Procedures. Structural Engineering International, 16(2), 113–117. DOI:10.2749/101686606777962477.

[30] Tagel-Din, H., and Meguro, K. (2000a). Applied element method for dynamic large deformation analysis of structures. Struct. Eng. Earthquake Eng., 17(2), pp. 215-224.

[31] Tagel-Din, H., and Meguro, K. (2000b). Applied element method for simulation of nonlinear materials: Theory and application for RC structures. Struct. Eng. Earthquake Eng., 17(2), 123s-148s.

[32] The Egyptian code for planning, designing, and implementing bridges and overpasses (2015).

[33] Wallace, J. W., Eberhard, M. O., Hwang, S. -J., Moehle, J. P., Post, T., Roblee, C, Stewart, J. P., and Yashinsky, M. (2001). Highway Bridges. Earthquake Spectra: Chi-Chi Earthquake Reconnaissance Report, 17 (SI), pp. 131-152.

[34] Wibowo, H., Reshotkina, S. S., and Lau, D. T. (2009). Modeling Progressive Collapse of RC Bridges during Earthquakes. *Proceedings of CSCE Annual General* Conference 2009: On the Leading Edge, St. John's, NL, Canada, May 27-30, Paper No. GC-176, 11.