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Comparing The Dynamic Properties of 1D, 2D, and 3D Models For Concrete Box-grider Bridge of 40-meter SPAN

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ABSTRACT Concrete box-girder is considered a rigid thin-walled structure, which is subject to deformation and forces in three-dimensional directions. However, it is commonly modeled as a 1D structure for design practicality, which influences the numerical results of its dynamic properties when compared to that of real-time SHMS and field tests. This study modeled the concrete box-girder structure as 1D (frame), 2D (shell), and 3D (solid) elements with *MIDAS Civil 2019,* in order to observe how the dynamic properties differ among the three models. Furthermore, it was modeled and analyzed as linearly elastic material because the allowable deflection and stress are limited by the design code. The dynamic properties obtained from these 3 models were compared with those obtained from real-time SHMS and field tests. It was observed that both natural frequency and period of 2D and 3D models were close to those of real-time SHMS and field test, but that of 1D was slightly larger, indicating that it provided natural frequency and structural rigidity that was slightly overestimated compared to the reality. In contrast to the 2D and 3D models, the structure was accounted to have a uniform cross-sectional rigidity along the transverse direction in the 1D model. This is the reason the 1D model seems to have higher structural rigidity and highest natural frequency compared to the other two models. This study therefore recommended that the design practice requires the designer's discretion when using the 1D model.

KEYWORDS Comparison; Dynamic; Modeling; Box-Girder; Concrete.

1 INTRODUCTION

Bridges are one of the infrastructures most needed in archipelago countries such as Indonesia while concrete box-girders are one of the most commonly used types for bridge decks. Theoretically, a concrete box-girder is considered a thin-walled structure subject to deformations and forces in three-dimensional directions due to the distributed dead and live loads. However, this structure is practically designed and treated as a 1D line element structure, in which the deformations and forces in the transversal direction are considered to be uniform. This design approach is preferred by most civil structural designers, particularly for basic design purposes because its shorter running time efficiently simplifies the design calculations compared to the 2D and 3D models. It is important to note that the differences among 1D, 2D, and 3D models have been explored with the real test results as observed in many aspects, such as the dynamic properties, consisting of natural frequencies and periods. Therefore, this study was conducted to examine and compare the dynamic properties of the three models with that of real-time SHMS and field tests.

Carrera *et al.* (2015) compared 1D, 2D, and 3D models and discovered that the 1D model yielded the highest natural frequency value among all modeling types, indicating that it provided higher structural rigidity than the 2D and 3D. This is because the 1D model does not consider the local buckling effect which usually occurs in thin-walled structures. However, the numerical differences among 1D, 2D, and 3D models were minimized by adding the diaphragm as the cross-sectional stiffener. Furthermore, Ibrahim and Suhendro (2004) studies the numerical differences in reinforced concrete T-beams that were modeled as 2D plane stress and 3D solid element in linear and non-linear states, and the results were validated experimentally. It was concluded that the 2D plane stress model produced a stiffness that is slightly higher than the 3D solid model, indicating that 2D and 3D models are likely to give quite satisfying numerical results for structures consisting of planar elements like T-beam but the 3D solid model was still the best approach for modeling.

Recently, Ling *et al.* (2020) found that the numerical deflections of reinforced concrete hollow beams modeled as 3D solid are almost unreliable compared to experimental deflections. This inaccuracy was obtained because several issues were not considered in the modeling, such as meshing size in which no convergence test was performed, material properties, and steel-concrete bonding. Effendi (2020) considered the non-linear effect on the modeling of reinforced concrete when examining its flexural behavior, and found a closely identical result between experimental and numerical models. It becomes clear that when modeling the RC structure, non-linear effects have to be considered in order to obtain realistic results since RC structural rigidity is not constant due to its crack section behavior. When it is impossible to determine that the structure is linearly elastic, the non-linear effects need to be considered in the modeling. This deduction also applies to pre-stressed concrete structures.

Miyamoto *et al.* (2000) studied the dynamic properties of concrete box-girder under prestressing force and discovered that the first vibration mode shape of the structures before and after stressing was identical, with a slight natural frequency difference between these stages. This is consistent with Hamed and Frostig (2006), which concluded that the prestressing force has no significant influence on the natural frequency of prestressed concrete under non-linear conditions. Aloisio (2021) examined the structural rigidity under the influence of prestressing force and discovered that the Young's modulus of all prestressed concrete samples showed a nearly constant elasticity at all increasing loads, thereby indicating that the rigidity was not affected by prestressing force. Furthermore, Atmaca (2019) compared the numerical natural periods of reinforced and prestressed concrete girders with identical dimensions and properties under linear and non-linear conditions and observed that the vibrational modes of the two structures are identical. However, the natural period obtained from the non-linear numerical analysis was slightly larger compared to the linear, indicating that the non-linearity only influenced the dynamic properties of the prestressed concrete structure to a certain extent.

Suhendro (1990) found that the insignificant effect of prestressing forces on structural rigidity was analogous to the steel column behavior subjected to axial loads under imperfections. The differences in dynamic properties between linear and non-linear analyses were caused by stiffness changes due to axial forces and eccentricity. These differences were negligible when the structure was loaded in the linearly elastic range, in which its rigidity was constant and the deformation was relatively small. However, when the axial force was increased beyond the elastic range, the structure simultaneously experiences an increase in deformation and a decrease in stiffness. At this stage, the large deformation occurred non-linearly, implying that non-linear analysis is required. This effect was also observed in recent studies by Effendi (2020) and Ling *et al.* (2020). Moreover, the large displacements are unlikely to occur in prestressed girders since both deformation and stress in the concrete are practically limited by codes in order to avoid excessive deformation and crack. This implies that the differences in dynamic properties between linear and non-linear analyses were insignificant, hence linear analysis was performed in numerical modeling for simplicity.

It is important to note that the concrete box-girder is still preferably modeled as a 1D element for practical purposes despite the different dynamic properties of the thin-walled structure in all model types, and particularly the overestimated rigidity of the 1D model. Currently, there have been no studies that compared the structural dynamic properties of 1D, 2D, and 3D model in concrete box-girder structures. This study therefore examines the dynamic properties obtained from each model type and aims to help the readers in discerning their differences when compared to both real-time and field test results in order to have better discretion regarding dynamic properties when using the 1D model in the future.

2 METHODS

A comparative method was used in this study and the concrete box-girder structure was modeled into 1D, 2D, and 3D using *MIDAS Civil 2019* in order to obtain the most dominant natural frequency and period, being the 1st mode from each model. The structure was modeled respectively as 1D or line beam, 2D, and 3D or shell and solid element, with their degrees of freedom as shown in Figures 1 to 3. The object utilized was a PC-box girder in Ujung Pandang, Makassar, South Sulawesi, Indonesia, with a concrete grade of K-500, a 40-meter span, and a cross-sectional geometry as shown in Figure 4.

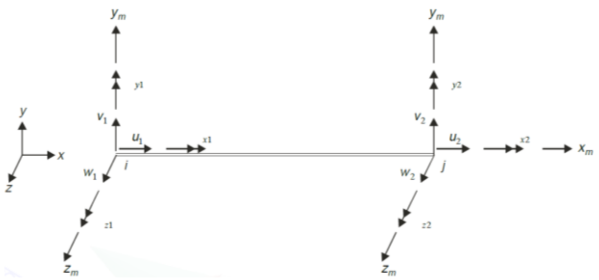

Figure 1. 1D line beam element (Bhavikatti, 2005)

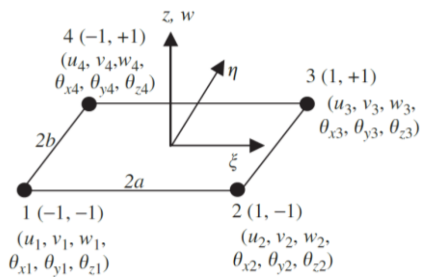

Figure 2. 2D shell element (Liu and Quek, 2003)

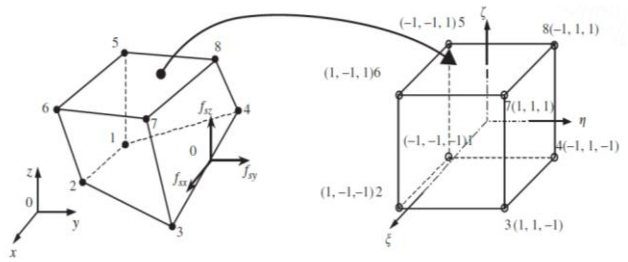

Figure 3. 3D solid element (Liu and Quek, 2003)

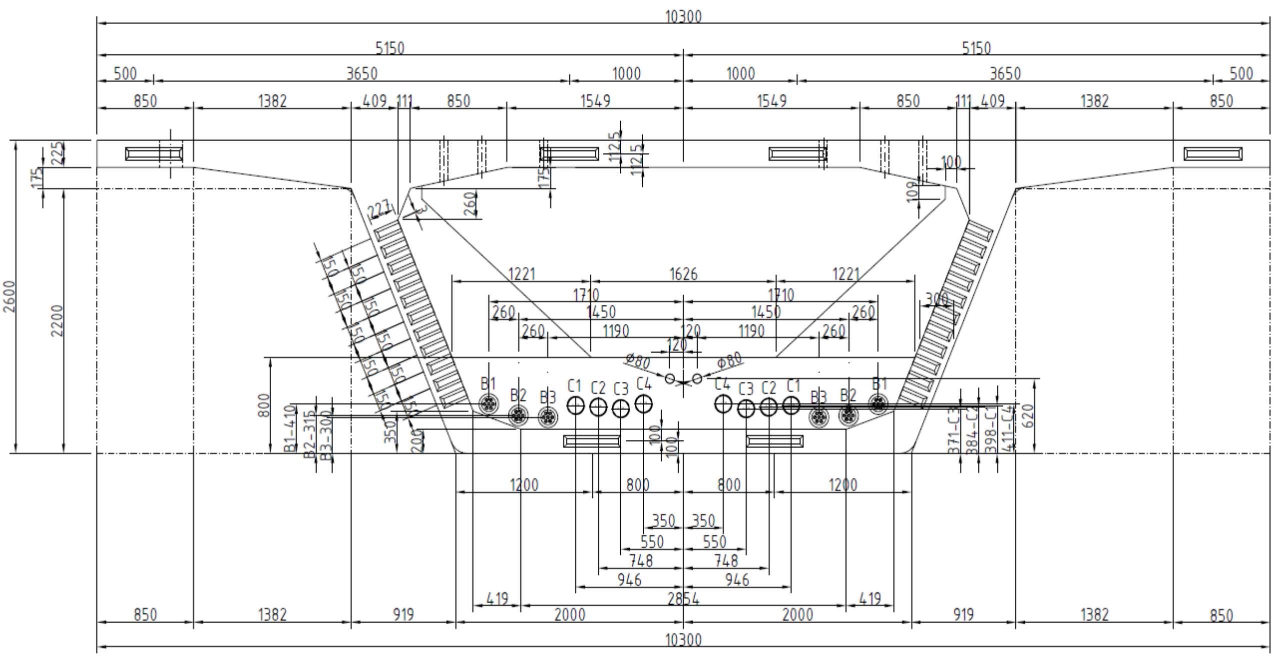

Figure 4. Sectional geometry of PC-box girder in Ujung Pandang, Makassar

The linear eigenvalue analysis was performed in MIDAS Civil 2019 in order to obtain the structural dynamic properties of each model, assuming that its rigidity was linearly constant due to the small displacement under prestressing force. Miyamoto (2000), Hamed and Frostig (2006), and Atmaca (2019) proved that the numerical error between linear and non-linear analyses under such conditions was negligible. The analysis was performed in each model with various element numbers in order to get the most accurate results. Furthermore, the natural frequency values and element numbers of each model were recorded and plotted into a chart from the iteration. As with the convergence test, the dynamic properties result to be obtained has to converge at a certain value, in which there was no significant numerical change despite the increasing element number.

The natural frequency and period obtained from the most dominant shape being the 1st mode of each modeling type above were compared with the results from real-time SHMS and field tests. Furthermore, a dynamic load test was performed with a colt-diesel truck dropped from a 250 mm high steel stack as shown in Figure 5, and the vibrations were recorded with an accelerometer. This method was applied in real-time SHMS and field tests using accelerometers installed in every quarter of the span. The results were then recorded and used as numerical validations obtained from structural modeling in *MIDAS Civil 2019*.

Figure 5. Dynamic load test method

3 RESULTS

The comparison of the natural frequencies obtained from each modeling type and element numbers were compiled in Table 1 below and were also plotted into charts, as shown in Figure 6 and 7. Based on Table 1, the 1D modeling type was still the best and most efficient method in terms of running time, since it has the shortest required runtime compared to the 2D and 3D models. Furthermore, the 1D model relatively reached convergence faster than 2D and 3D, in which its numerical result was closely converged or perfectly identical to others with larger element numbers.

Table 1. Structural dynamic properties of each model & test

1D (line beam)			2D (shell)			3D (solid)		
Element Number	Frequency (Hz)	Running Time (s)	Element Number	Frequency (Hz)	Running Time (s)	Element Number	Frequency (Hz)	Running Time (s)
0	0	0	0	0	0	0	0	0
8	4.11	10	174	3.6	18	580	4.07	50
12	4.29	12	352	3.58	37	828	4	61
18	4.29	9	1240	3.63	63	1188	3.98	72
30	4.29	12	2296	3.77	113	1908	3.97	105
54	4.29	18	4408	3.82	217	2948	3.97	157

Similar to the convergence test method, all results in Table 1 were plotted in a graph to obtain the most accurate values of the natural period from each modeling type, which have converged to a certain natural frequency value, as shown in Figures 6 and 7. The respective natural frequencies of 1D, 2D, and 3D models were 4.29 Hz, 3.77 Hz, and 3.98 Hz. Figures 8 to 10 show the results of these three models obtained from *MIDAS Civil 2019* using convergent element numbers. It was observed that the most dominant vibration mode shape or 1st mode of all modeling types was vertical, thereby indicating that they all provided identical results with similar structural properties and geometry.

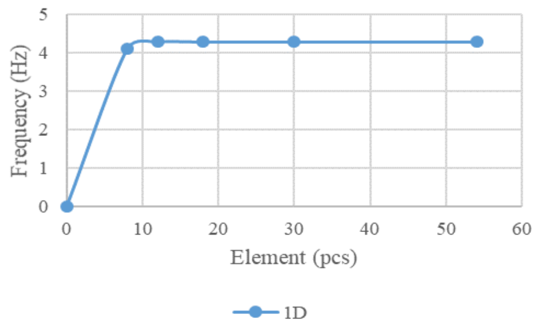

Figure 6. Convergence for natural frequency of 1D model

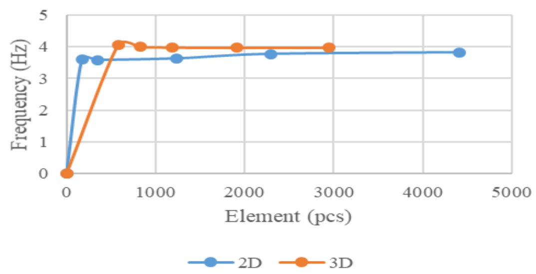

Figure 7. Convergence for natural frequency of 2D and 3D models

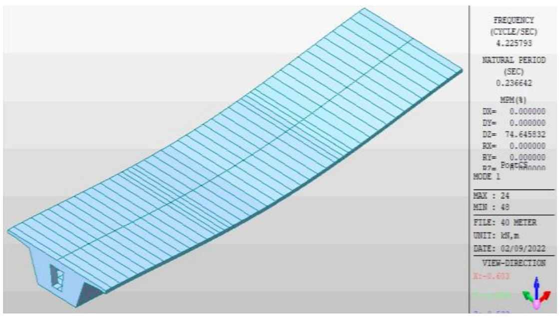

Figure 8. Mode shape of 1D model (line beam element)

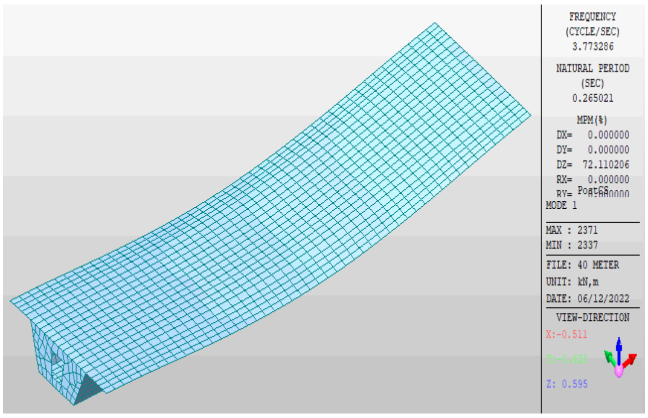

Figure 9. Mode shape of 2D model (shell element)

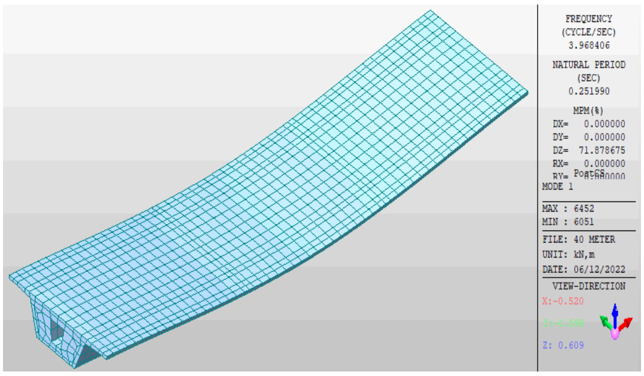

Figure 10. Mode shape of 3D model (solid element)

The *MIDAS Civil 2019* numerical results were further compared with the outcome of the field test and real-time SHMS for validation, which include 3.91 Hz and 3.81 Hz, respectively. Figures 11 and 12 show the results obtained from these two tests.

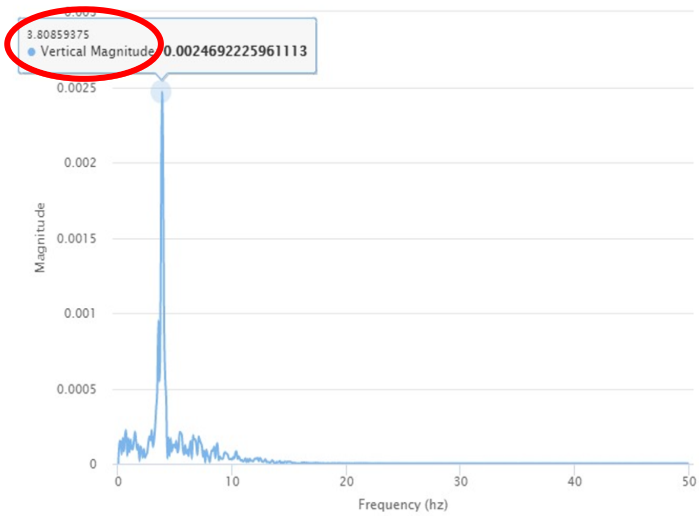

Figure 11. Real-time SHMS result (circled in red)

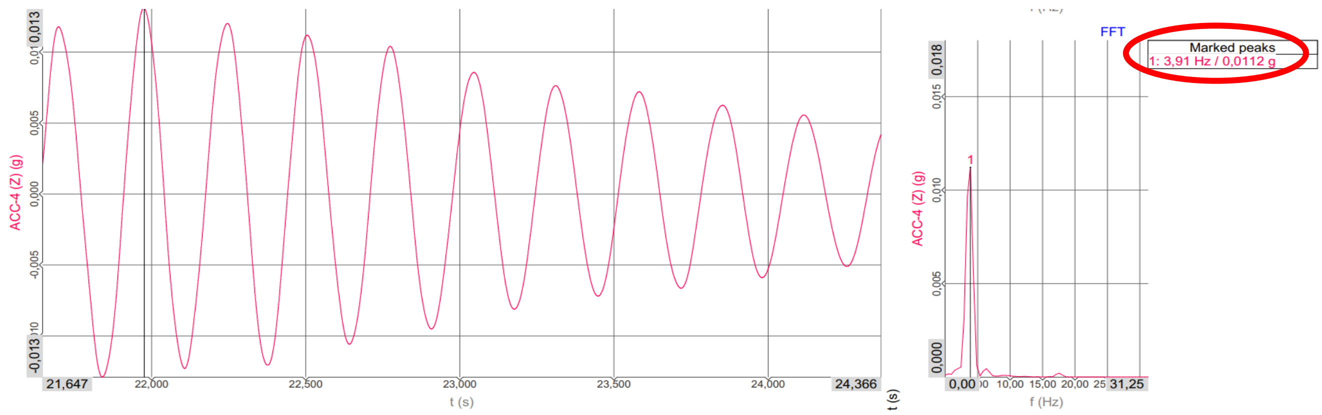

Figure 12. Field test result (circled in red)

Table 3 shows the dynamic property's summary, which consists of natural frequency and period. Its values were obtained from each modeling type with specifications explained in Section 2. The natural period in this case was considered as the reciprocal value of the frequency.

Table 2. Structural dynamic properties of each model & test

Model Type & Test Result	Natural Frequency (Hz)	Natural Period (second)
1D Model	4.29	0.233
2D Model	3.77	0.265
3D Model	3.98	0.251
Field Test	3.91	0.256
Real-time SHMS	3.81	0.263

It was observed that dynamic property values in 1st mode of each modeling type were close to each other. These values were also close to real-time SHMS and field test results, indicating that the models are reliable and valid to be considered, even though the highest frequency occurred only in the 1D model. Regarding the 2D and 3D models, the results are respectively identical to real-time SHMS and field tests. This indicates that these models are more preferred to represent the real structural conditions than the 1D model, even though they required longer running time.

4 DISCUSSION

The results above have shown that concrete box-girder had the identical vibration mode shape in all types of modeling. This is similar to the dynamic properties, consisting of natural frequency and period, in which the values obtained from all modeling types are close to those of real-time SHMS and field tests. Meanwhile, the 1D model produces a slightly higher natural frequency than the 2D and 3D models, yet they are closer to the real-time SHMS and field test results. This showed that the 1D model yielded an overestimated natural frequency for the thin-walled structure such as concrete box-girder, indicating that it is too high for the structure's stiffness.

This overestimated natural frequency was technically due to the different behavior of thin-walled structures when modeled as 1D. In reality, the thin-walled structure has much less cross-sectional area than that of its void, thereby making it undergo additional local deformation and stress that is impossible to detect with the 1D model. The occurrence of local deformation proved that the cross-sectional rigidity was very different from that of line beam elements, as it is less than that of the 1D model. It is important to note that quite noticeable errors tend to exist between 1D and other higher model types unless the thin-walled section is stiffened to minimize such undetected local deformation. This explanation was supported by Carrera *et al.* (2015), stating that the transverse rib's application in the cross-section of a thin-walled structure increased its sectional rigidity and reduce the numerical error between 1D and real structural models represented by 2D and 3D.

Carrera *et al.* (2015) also discovered that 2D and 3D models yielded numerical results that are close to each other, with 1D model rigidity being higher than the other two. This is consistent with Ibrahim and Suhendro (2004), proving that 2D plane stress and 3D solid model yielded close numerical results to that of an experiment. It denotes that the 2D and 3D models produce more satisfying and closer numerical results compared to the 1D in reality. It is also observed that the higher cross-sectional rigidity of the 1D model yielded an overestimated structural rigidity or a higher natural frequency when compared to the other models. Therefore, the thin-walled structure needs to be modeled as 2D (shell) and 3D (solid) element rather than a 1D model to obtain the more accurate rigidity and dynamic properties when compared to the real-time and field tests.

Despite the linear analysis assumption in the model, both the real-time and field test results are interestingly close to that of the numerical, particularly for the 2D and 3D, thereby proving that prestressing force effect on structural rigidity was quite insignificant. Miyamoto *et al*. (2000), Hamed and Frostig (2006), Atmaca (2020), and Aloisio (2021) also concluded that prestressing force had no significant impact on structural rigidity. According to Suhendro (1990), it occurred only when the structure acts linearly elastic under combined loads and prestressing force, thereby resulting in constant rigidity and natural frequency. It was concluded that as long as the concrete box-girder stress and deformation do not exceed its permitted limit, the dynamic properties are analyzable using linear analysis, provided the prestressing force effect on structural rigidity is insignificant. However, this deduction was not applicable when the concrete structure acts as a crack-section such as reinforced concrete, since its tensile stress always exceeds the standard, thereby resulting in a change in cross-sectional rigidity during loading. This signifies that the noticeable error between numerical and experimental results tends to occur as found in Ling *et al.* (2020) until the non-linear analysis was applied according to Effendi (2020).

It is important to note that the overestimate structural rigidity and natural frequency need to be treated with caution as the numerical error produced by the 1D model is likely to give a false impression that the structure is more rigid than the reality, even though the difference is slightly higher. This falsely overestimated rigidity is capable of influencing the designer's engineering judgment during deformation checking, in which the thin-walled structure appeared stiffer and less deformed compared to the reality under combined service loads. Therefore, the designer's discretion is highly advised when using the 1D model. The addition of a cross-sectional transverse diaphragm, as proven by Carrera *et al*. (2015), was considered as an alternative to stiffen its rigidity, in order to improve the results obtained from the 1D model for it to be close to those of 2D and 3D models. This helps to achieve the design practicality and numerical accuracy simultaneously.

5 CONCLUSION

This study compared the dynamic properties and vibration mode shape of the concrete box girder, which was modeled using linear eigenvalue analysis as 1D or line beam, 2D, and 3D or shell and solid elements, respectively. It was observed that the structure acted as a linearly elastic element under prestressing force and combined loads because both the real-time and field test yielded a very close result to numerical modeling. This showed the possibility of analyzing dynamic property using linear analysis. The authors discovered that the most dominant vibration mode shape, being the 1st mode of concrete box-girder structure was only in the vertical global axis direction, regardless of its modeling type. Meanwhile, the 2D and 3D models yielded a very close natural frequency value to both the real-time SHMS and field tests, but the natural frequency obtained from 1D produced slightly higher values compared to others. The overestimated frequency indicated that the structure falsely appears more rigid than in reality, as the result was directly proportional to structural rigidity. This falsely higher result occurred because the 1D modeling assumed the structure acts as a rigid cross-section with no local deformation. Therefore, designer's discretion is highly recommended when selecting the 1D model for designing thin-walled structures like concrete box-girder. The designer needs to increase the cross-sectional rigidity of the 1D by adding the transverse diaphragm which helps to minimize the error between the model and other modeling types.

DISCLAIMER

The authors declare no conflict of interest.

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REFERENCES

Aloisio, A., 2021. Aspects of Vibration-Based Methods for the Prestressing Estimate in Concrete Beams with Internal Bonded or Unbonded Tendons. *Infrastructures 2021*, 6, 83. https://doi.org/10.3390/ infrastructures6060083

American Association of State Highway and Transportation Officials, 2017. *AASHTO LRFD Bridge Design Specification, Eighth Edition*. American Association of State Highway and Transportation Officials 444 North Capitol Street, NW, Suite 249, Washington, DC 20001.

Atmaca, B., 2019. Comparison of Dynamic Characteristics of Prestressed and Reinforced Concrete Beams. *Düzce University Journal of Science & Technology*, 7 (2019) 37-44.

Bhavikatti, S.S., 2005. *Finite Element Analysis*. New Age International (P) Ltd., Publishers 4835/24, Ansari Road, Daryaganj, New Delhi – 110002.

Carrera, E., Pagani, A., Zangallo, F., 2015. Comparison of Various 1D, 2D, and 3D FE Model for The Model of Thin-walled box with Transverse Ribs Subjected to Load Factors. *Elsevier BV*, Finite Element in Analysis and Design 95 (2015) 1-11, http://dx.doi.org/10.1016/j.finel.2014.10.004

Direktorat Jenderal Bina Marga, 2021. *Panduan Praktis Perencanaan Teknis Jembatan 02/M/BM/2021*. Kementerian Pekerjaan Umum dan Perumahan Rakyat, Jakarta.

Effendi, M.K., 2020. Non-Linear Finite Element Analysis of Flexural Reinforced Concrete Beam using Embedded Reinforcement Modeling. Journal of Civil Engineering Forum, September 2020, 6(3): 271-284, DOI 10.22146/jcef.55960, ISSN 2549-5925 (online), 2581-1037 (print).

Hamed, E., Frostig, Y., 2006. Natural Frequencies of Bonded and Unbonded Prestressed Beams – Prestressed Force Effects. *Elsevier Ltd.*, Journal of Sound and Vibration 295 (2006) 28–39, DOI: 10.1016/j.jsv.2005.11.032.

Ibrahim, E.S.M., Suhendro, B., 2004. Comparison Study on The Accuracy of Reinforced Concrete T-Beam Analyzed by Using Plane Stress and Solid Finite Elements. Yogyakarta: Master Thesis Report. Department of Civil and Environmental Engineering. Universitas Gadjah Mada.

Ling, J.H., Chan, L.L., Leong, W.K., Sia, H.T., 2020. The Development of Finite Element Model to Investigate the Structural Performance of Reinforced Concrete Hollow Beams. Journal of Civil Engineering Forum, May 2020, 6(2): 171-182, DOI 10.22146/jcef.53301, ISSN 2549-5925 (online), 2581-1037 (print).

Liu, G.R., Quek, S.S., 2003. *The Finite Element Method – A practical course*. Elsevier Science Ltd. Butterworth-Heinemann, England.

Miyamoto, A., Tei, K., Nakamura, H., Bull, J.W., 2000. Behaviour of Prestressed Beam Strengthened with External Tendons. *Journal of Structural Engineering*, Vol. 126, No. 9, September, 2000. ASCE, ISSN 0733-9445/00/0009-1033–1044.

Suhendro, B., 1990. Analisis Buckling pada Struktur dengan Finite Element Method. *Media Teknik Edisi No. 1 Tahun XII*, April 1990, No. ISSN 0216-3012.