Comparative analysis of different numerical models of a steel radial gate

Krzysztof Brusewicz[1] , and *Robert* Jankowski[1,*]

[1]Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Narutowicza 11/12, 80-233 Gdańsk, Poland

Abstract. Hydrotechnical structures are important components in water management system and general flooding safety. Their reliability should be ensured since potential damage might lead to catastrophic consequences. Weir gates are considered to be highly vulnerable elements of each hydro power plant, with regard to its dynamic resistance. The aim of the paper is to compare different numerical models and their influence on the results of a computational modal analysis of a steel radial gate. The investigation has been conducted for models using beam and shell elements, while assuring the same geometry, material properties and boundary conditions. The results of the comparative computational analysis indicate that the eigenmode shapes are similar for both models, while the corresponding eigenfrequencies are considerably different. These differences are important from the point of view of dynamic analysis, especially that the first eigenfrequency falls within the energy range typical for earthquakes and mining tremors.

1 Introduction

Hydrotechnical structures are planned for long term operation and require a large investment of money and time to build and manage, which is not the same as for other structures [1, 2]. Their placement and reliability are a vital component in a country water management system and general flooding safety. In this regard, hydro power plants are considered among the most important structures. They provide the country with cheap and accessible electricity; they are also a part of general water management system. Their reliability is of great importance, therefore they should be able to withstand extreme conditions. In order to secure the infallibility of the structure, several analyses should be carried out, including the response to dynamic loads caused by earthquakes or mining tremors.

One of the most vulnerable elements of each hydro power plant, with regard to dynamic resistance, is the weir gate. Weir gates provide the necessary water accumulation level needed for energy production [3]. The failure of a weir gate may cause loss in production or even lead to major damage, with even catastrophic consequences. As mentioned by Peilert in [4], steel radial gates are superior to normal vertical plates with regard to both their weight and construction time. When comparing both constructional solutions for the same

[*] Corresponding author: jankowr@pg.edu.pl

weir, the radial gates tend to have mass up to 50% lower than vertical plate gates. Similar statements on this subject can also be found in other works (see [3, 5], for example).

In constant development of new tools and software, the struggles of engineers as well as designers take a new shape. The previous restrictions connected with limited hardware strength limiting the calculations have almost completely vanished. The modern researcher can apply various software to suit the needs well, however it is still required not to trust them blindly and to verify the obtained results. The aim of the article is to compare two typical element types used in a numerical model of a steel radial gate in order to find the differences between them in light of modal analysis. The Lanczos method within the ABAQUS software has been used in the study [6, 7].

2 Numerical models

Two geometrically identical (see Figure 1) numerical models have been created. Both of them have the same boundary conditions and affiliated loads. The only difference lies in the chosen element types. The first computational model has been constructed with the use of beam profiles defined by the user. The second model consists of shell elements only, meaning that each beam is made of several shells combined together into a single profile. The connections in both models have been modelled as ties, both with the same nodal values.

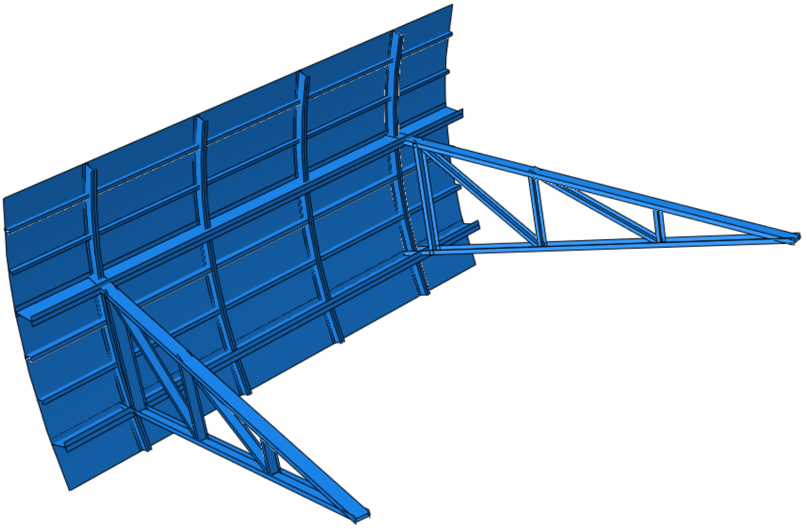


Fig. 1. The model geometry used for modal analysis.

2.1 Geometry and materials

The total height of the steel radial gate, considered in the study, is 4.3 m. Its width is equal to 8.0 m. The radius from the bearing to the radial plate is 6.5 m. The radial plate, which is 7 mm thick, is supported by vertical I180 beams and horizontal C80 and C140 beams. The structure main bearing beams are two I360 girders connected with the arms of the gate. The arms are C180 and C140 profiles. The details concerning the geometry and profiles can be found in [1]. The dimensions of all the profiles are presented in Table 1 (see also description of symbols in Figure 2).

Table 1. Profiles used in the gate.

Profile	h	s	z	t
	[mm]	[mm]	[mm]	[mm]
I180	180.00	82.00	10.00	6.90
I360	360.00	143.00	20.00	13.00
C80	80.00	45.00	8.00	6.00
C140	140.00	60.00	10.00	7.00
C180	180.00	70.00	11.00	8.00

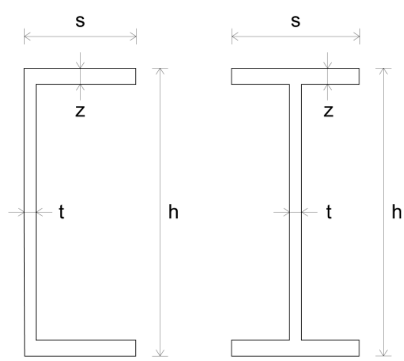


Fig. 2. Used element profiles.

2.2 Element types and mesh

The discretization of the computational mesh for both models is similar. The mesh has been created using global size control. The analysis has been conducted for elements of approximate area of 50 mm^2 for beams and 100 mm^2 for the radial plate. The first model has two types of elements. It employs shell elements (4-node doubly curved shell with reduced integration, hourglass control, finite membrane strains - ABAQUS codename S4R) so as to model the radial plate. On the other hand, beam elements (2-node linear beam in space with the codename B31) were applied for modelling the supporting beam profiles. The second model applies only shell elements for modelling all members of the structure.

2.3 Boundary conditions

An important part of the numerical model of steel radial gates is related to boundary conditions. Due to the possible movement between the radial gate and pillars (the gate is connected to them via bearings), the horizontal displacement is allowed. It is also important to mention that the gate cannot move from its bearings (if such a case occurs, a major disaster could take place). Therefore, two types of boundary conditions have been applied in the model. The first one includes fixed displacements in the bearings (see Figure 3). The second boundary condition allows the vertical displacements of the radial bottom edge to be blocked.

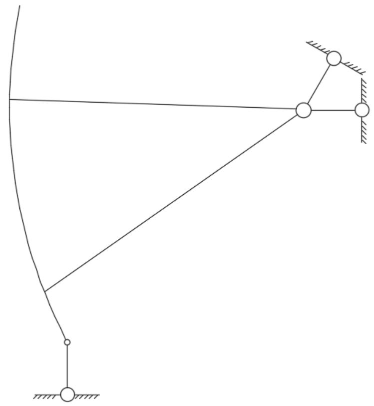


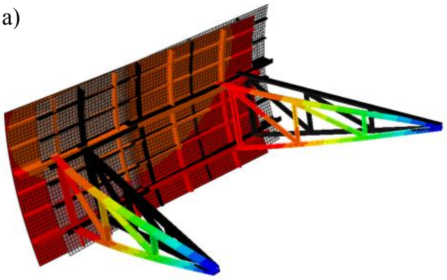
Fig. 3. Boundary conditions in the model.

3 Results and discussion

The conducted modal analysis has resulted in 10 eigenmodes and eigenfrequencies for each of the models. Selected eigenmode shapes are presented in Figures 4-7. The comparison between the eigenfrequencies for both models is shown in Table 2.

The results shown in Figures 4-7 indicate that the eigenmode shapes are similar for both models. On the other hand, as clearly seen in Table 2 that the corresponding eigenfrequencies are considerably different. In the case of the first eigenfrequency, the difference is equal to 0.84 Hz, what stands for the increase by as much as nearly 62% when comparing the shell model with the beam model. This result is very interesting and important from the point of view of the dynamic properties of a structure [8, 9]. The low frequency suggests that the analysed structure is susceptible to dynamic loads, such as earthquakes or mining tremors, which carry most of their energy in the 1-5 Hz range [10-13]. It indicates, that in the case of such dynamic loads, it is possible for the radial plate to pound against pillars (compare [14-16]) causing unsealing, deformation, other difficult to repair damage [17] or even the destruction of the structure. From this point of view, relatively large difference in the eigenfrequency value between the beam and shell model is really important for obtaining the accurate response from the dynamic analysis.

a)



b)

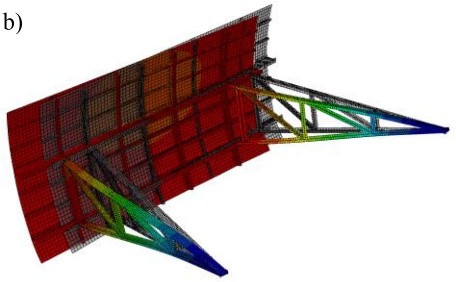


Fig. 4. First eigenmode shape: a) beam model b) shell model.

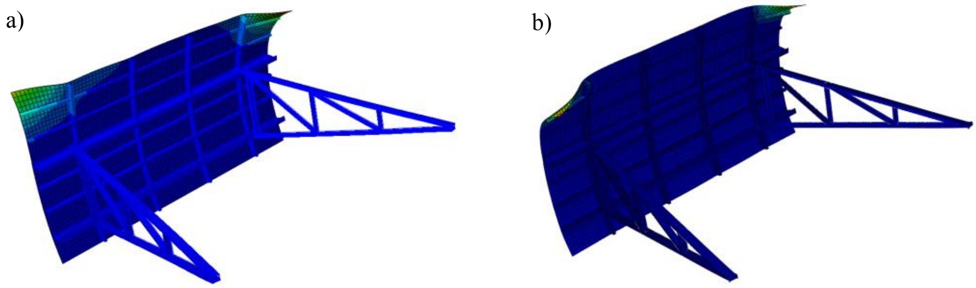


Fig. 5. Second eigenmode shape: a) beam model b) shell model.

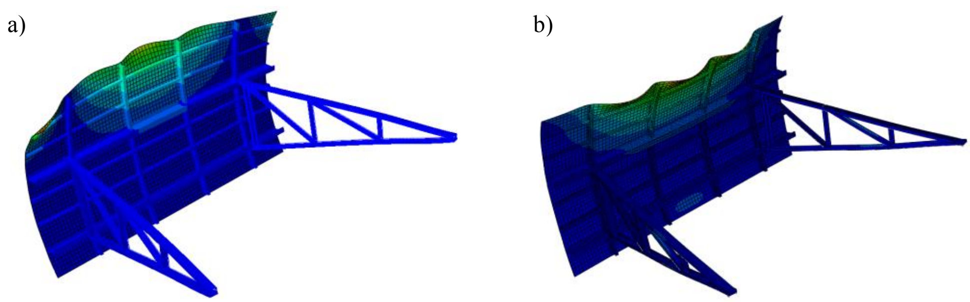


Fig. 6. Fourth eigenmode shape: a) beam model b) shell model.

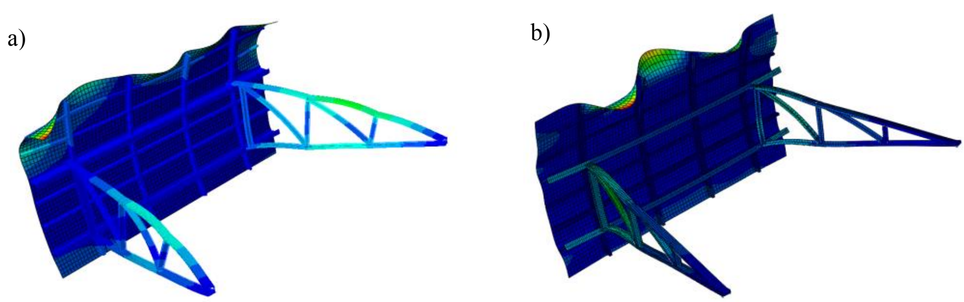


Fig. 7. Tenth eigenmode shape: a) beam model b) shell model.

Apart from the first natural frequency, the rest of the eigenfrequencies have values larger than 10 Hz. Such high frequencies occur rather seldom as components of external excitations [8], so the probability that they will be induced in the structure is very low. Also, it can be seen from Figures 4-7 that the shapes of the higher eigenmodes represent mainly local forms of vibrations (see also [10]).

While comparing the frequencies in Table 2 we can see the cases when one model shows greater stiffness than the other one. The first eigenfrequency value is higher for the shell model than for the beam model, suggesting that the arms modelled with shell elements have a higher horizontal resistance in comparison to beam elements. The frequency values for the next two eigenmodes are lower for the shell model than for the beam model. Since these modes represent vibrations of the radial plate upper corners, the results indicate that the application of beam elements results in the increase in stiffness of the supporting vertical members. However, in the case of eigenmodes no. 4-10, the frequency values are higher for the shell model than for the beam model, as it can be observed in Table 2.

Table 2. Eigenfrequencies for both models.

No.	Beam model	Shell model	Difference
	[Hz]	[Hz]	[%]
1	1.34	2.17	61.94
2	15.23	13.64	10.44
3	15.40	13.67	11.23
4	15.98	16.59	3.82
5	17.44	20.49	17.49
6	18.40	21.86	18.80
7	20.86	22.46	7.67
8	22.92	23.45	2.31
9	23.18	23.68	2.16
10	24.49	25.54	4.29

4 Conclusions

The results of a modal analysis of a steel radial gate, using two different numerical models, have been presented in this paper. The computational investigation has been conducted for models with beam and shell elements, while assuring the same geometry, material properties and boundary conditions.

The results of comparative analysis indicate that the eigenmode shapes are similar for both models, while the corresponding eigenfrequencies are considerably different. These differences are important from the point of view of analysis of structure exposed to dynamic loads. The above statement is especially important in the case of the first eigenfrequency, since it falls within the energy range typical for earthquakes and mining tremors. On the other hand, the rest of the determined eigenfrequencies are somehow large and the probability of being induced is relatively low, since such frequencies occur rather seldom as components of external excitations.

Generally speaking, the application of shell elements allows us to model different structures more precisely comparing to the case when beam elements are used. The resulting differences in eigenfrequencies between two models are mainly attributed to the way of modelling using different element types in ABAQUS software. Moreover, boundary conditions and connections between elements have been idealized in both models. It should be underlined, that accuracy verification of the numerical model should always be conducted comparing the numerical results with the experimental ones. Therefore, further study, focused on experimental tests, is planned to be conducted so as to confirm the numerical results obtained. After experimental verification, a full non-linear dynamic analysis are also scheduled (including some stochastic issues [18-20]) so as to verify the seismic resistance of different types of steel radial gates.

The authors would like to thank TASK CI for the opportunity to use ABAQUS software. Calculations were carried out at the Academic Computer Centre in Gdańsk

References

1. Z. Boretti, *Konstrukcje stalowe w budownictwie wodnym* (Arkady, Warszawa, Poland, 1968)
2. D. Kowalski, B. Grzyl, A. Kristowski, The cost analysis of corrosion protection solutions for steel components in terms of the object life cycle cost, Civil and Environmental Engineering Reports, **26**, 5-13 (2017)
3. K. Fanti, *Budowle piętrzące* (Arkady, Warszawa, Poland, 1972)
4. F.W. Peilert, *Zamknięcia jazowe o napędzie mechanicznym* (Arkady, Warszawa, Poland, 1957)
5. W. Depczyński, A. Szamowski, *Budowle i zbiorniki wodne* (Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, Poland, 1999)
6. O.C. Zienkiewicz, R.L. Taylor, *The Finite Element Method* (Butterworth-Heinemann, Oxford, UK, 2002)
7. K. Brusewicz, R. Jankowski, Modal analysis of a fish-belly flap type of steel water gate**,** 11th Conference “Shell Structures: Theory and Applications”, Gdańsk, Poland, 11-13.10.2017, **4**, 351-354 (2018)
8. A. Chopra, *Dynamics of Structures: Theory and Applications to Earthquake Engineering* (Prentice Hall, Englewood Cliffs, USA, 1995)
9. M. Ebrahimian, M.I. Todorovska, T. Falborski, Wave method for structural health monitoring: testing using full-scale shake table experiment data. Journal of Structural Engineering, 143, article no. 04016217 (2016)
10. W.F. Chen, C. Scawthorn, *Earthquake Engineering Handbook* (CRC Press, Boca Raton, USA, 2003)
11. J. Przewłócki, W. Knabe, Settlement of a soil stratum subjected to an earthquake, International Journal for Numerical and Analytical Methods in Geomechanics, **19**, 813-821 (1995)
12. Z. Zembaty, Rockburst induced ground motion - a comparative study, Soil Dynamics and Earthquake Engineering **24**, 11-23 (2004)
13. E. Maciag, K. Kuźniar, T. Tatara, Response spectra of the ground motion and building foundation vibrations excited by rockbursts in the LGC region, Earthquake Spectra, **32**, 1769-1791 (2016)
14. C.G. Karayannis, M.J. Favvata, Inter-story pounding between multistory reinforced concrete structures, Structural Engineering and Mechanics **20**, 505-526 (2005)
15. H. Naderpour, R. C. Barros, S.M. Khatami, R. Jankowski, Numerical study on pounding between two adjacent buildings under earthquake excitation, Shock and Vibration, **2016**, article ID 1504783 (2016)
16. P.C. Polycarpou, L. Papaloizou, P. Komodromos, An efficient methodology for simulating earthquake-induced 3D pounding of buildings, Earthquake Engineering and Structural Dynamics, **43**, 985-1003 (2014)
17. T. Falborski, R. Jankowski, A. Kwiecień, Experimental study on polymer mass used to repair damaged structures, Key Engineering Materials, **488-489**, 347-350 (2012)
18. R. Jankowski, H. Walukiewicz, Modeling of two-dimensional random fields, Probabilistic Engineering Mechanics, **12**, 115-121 (1997)
19. J. Przewłócki, *Problemy stochastycznej mechaniki gruntów. Ocena niezawodności* (Dolnośląskie Wydawnictwo Edukacyjne, Wrocław, Poland, 2006)

20. P. Sorn, J. Górski, J. Przewłócki, Probabilistic analysis of a space truss by means of a multidimensional variable description, Archives of Civil Engineering, **61**, 99-123 (2015)