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DESIGN ERRORS RESULTING FROM THE ADOPTION OF AN INCORRECT MODEL OF A STRUCTURE

BŁĘDY PROJEKTOWE WYNIKAJĄCE Z PRZYJĘCIA NIEWŁAŚCIWEGO MODELU KONSTRUKCJI

A b s t r a c t

The paper presents the design errors resulting from the adoption of an incorrect model of a structure as an example of real tanks. In addition, based on our own numerical analysis of a football stadium, the paper shows the differences between results obtained from the three-dimensional model – and other, more simplified schemes.

Keywords: 3D model, tank, football stadium

S t r e s z c z e n i e

W artykule zaprezentowano błędy projektowe wynikające z niewłaściwego przyjęcia modelu konstrukcji na przykładzie rzeczywistych zbiorników. Ponadto w oparciu o własną analizę numeryczną stadionu piłkarskiego pokazano różnice w wynikach uzyskanych z modelu trójwymiarowego – oraz innych, bardziej uproszczonych schematów.

Słowa kluczowe: model 3D, zbiornik, stadion piłkarski

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1. Introduction – contemporary design tools

Construction is one of the oldest expressions of human rational activities. Since man gave up his nomadic way of life, he began to erect buildings using various materials. The art of construction has evolved over the years from simple mud huts to enormous, engineering facilities.

The development of sciences such as mathematics, strength of materials and last, but not least, the information technology revolution, have resulted in the creating of computer programs that use different types of numerical methods. This has created completely new possibilities for designers and made it possible to exceed barriers not even thought of in the past.

This software is commonly used today in the design process of complex facilities whose operation is typically spatial. It allows creation of three dimensional models where all components are involved in the load carrying process. Simplified 2D analysis can lead to significant over-dimensioning or, even worse, to inappropriate assessments of a structure's response.

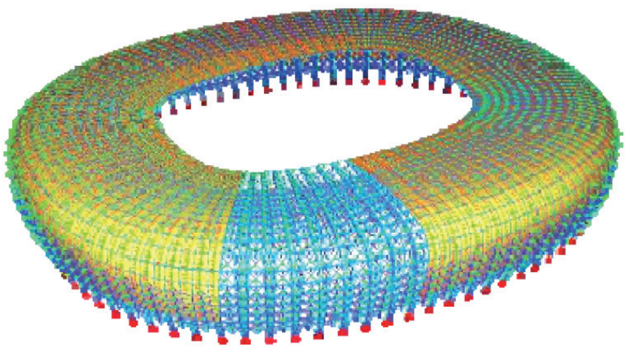

Fig. 1. Model of the structure of the stadium in Gdańsk – SOFiSTiK (5)

The contemporary, three-dimensional models (and 4D, used increasingly, which includes the time factor), in conjunction with the virtual reality technology, form a very important tool used not only in engineering practice, but also in the teaching process. They display in an intelligible manner, the features of the response of a structure. In the 21st century, access to specialised software is widespread, however, it should always be remembered that the use of software requires "the skills and knowledge to create economic and viable solutions"[1].

In the past, the massive character of a structure was a protection buffer for inaccurate models. The modern design has changed these relationships – advanced numerical models allow the design of light, simple and cost-effective facilities, consistent with Antoine de Saint-Exupéry's quotation: "The engineer knows that he has reached perfection not when there is nothing left to add, but when there is nothing left to remove".

[1] For more information, see (1).

2. Errors in the conical model of a reinforced concrete fermentation chamber ZKF roofing [2]

The structure and size of the tank is shown in Fig. 2. The roofing is in the form of a truncated cone, which consists of 44 prefabricated, reinforced concrete hollow-core rib plates, connected to each other with spandrel beams. The continuity of the circumferential reinforcement is provided by welded rods connection in the spandrels, while the L-shaped Ø6 reinforcement every 20 cm, connects the spandrel beam with the prefabricated element ribs (Fig. 3). At the top of the cone, there is a cross-reinforced concrete monolithic slab with a 50 cm thickness and a diameter of 6 m. The roofing is connected with the cylindrical shell by means of a circumferential ring.

As a result of biogas explosion, the tank suffered much damage and was out of operation. The damage observed included disruption of the connection between the prefabricated element ribs and the concrete topping. Moreover, the connection between the roofing and the cylindrical shell at the height of the ring was torn. Also, the ring was locally torn and displaced outwards along the plane of the connection with cylindrical shell (Fig. 4), the top plate was cracked along the perimeter and the cylindrical shell was cracked vertically beneath the ring.

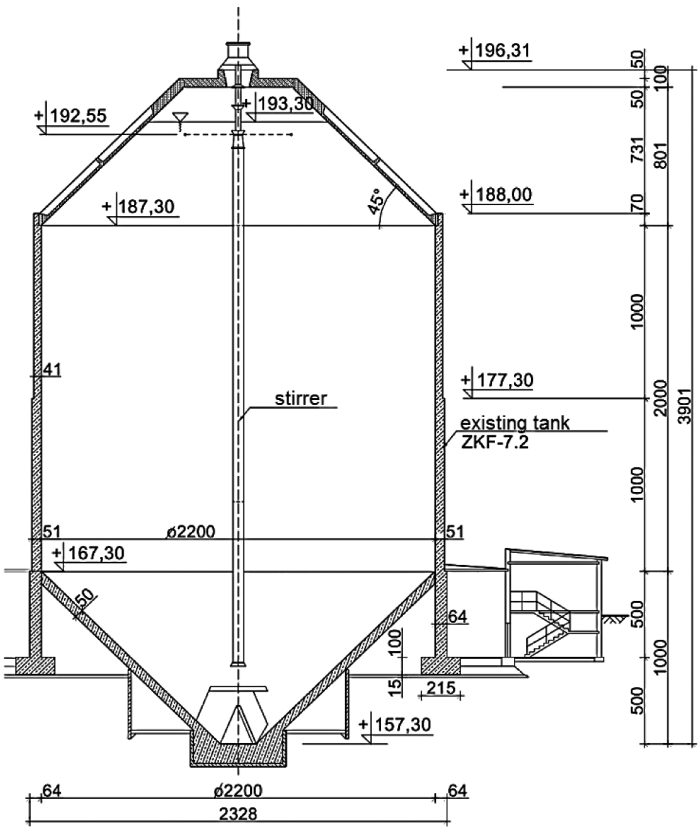

Fig. 2. Cross-sectional view of the tank (2)

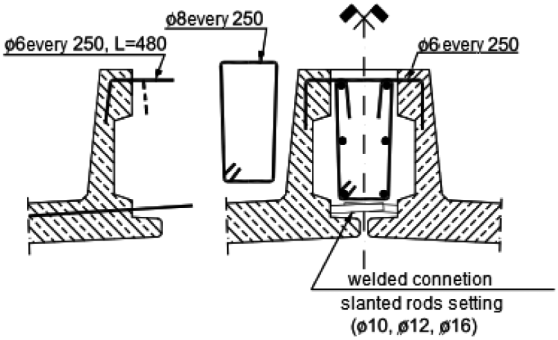

Fig. 3. Detail of the prefabricated elements connection (2)

One of the main causes of the extensive damages was the errors at the design stage – in creating the calculation model, to be more precise. After the roofing elements were made monolithic, a radial-wise ribbed coating with a thickness of 12 cm (rib height 55 cm) was created. Probably such a shape of the structure made the designers render the operation of the cone with vertical frames loaded with wastewater pressure. The consequence of this assumption was considering the shell spatial work only in the meridional direction, while disregarding completely the direction of the parallel.

In this direction, the reinforcement was determined for a scheme of a unidirectional slab supported on ribs and loaded with wastewater pressure at a variable level. The circumferential connections, as shown in Fig. 3, were the weakest link of the roofing structure. The effect was that they were damaged already in the initial phase of use, with a minimum overload (3% of the working load).

Fig. 4. Morphology of damages on the top of the tank (2)

The example discussed above shows how a lack of understanding of the work of a structure and the resulting adoption of its simplified model (two-dimensional frames), may lead to a structural disaster.

3. Errors in the model of a double-chamber reinforced concrete phosphorus tank (3)

Another example of a structure whose failure was caused by errors at the design stage is an underground double-chamber phosphorus storage tank, insulated with a 10-cm Styrofoam layer. Its geometry is shown in Fig. 5.

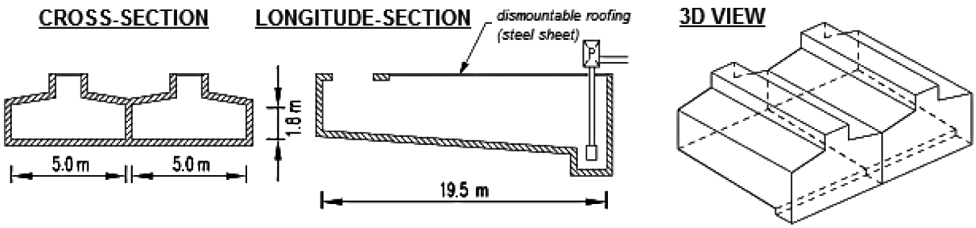

Fig. 5. Geometry of the analysed tank (3)

The phosphorus storage technology requires a water seal, with a water temperature of approx. 90°. The diagram of such a water seal has been shown in Fig. 6. Disregarding the thermal load was a fundamental error in the design documentation. In addition, certain technological loads were not taken into account, subsoil was not examined, and an incorrect structural model was adopted, which did not represent the actual spatial work of the tank.

The individual walls of the structure were treated as separate, bent beams, with no axial forces. The adopted model is shown below.

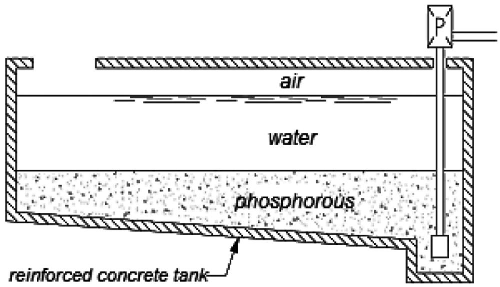

Fig. 6. Water seal diagram (3)

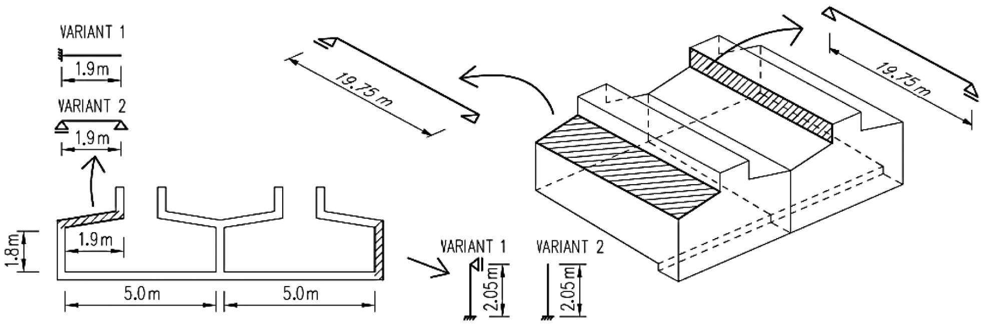

Fig. 7. Static diagrams included in the tank design (3)

4. Errors in the model of a three-chamber reinforced concrete tank in a wastewater treatment plant (4)

The reinforced concrete sewage tank consists of three chambers: one main and two smaller ones, the dimensions of which are presented in the diagram of tank structure (Fig. 8). The tank height is 4.15 m (calculated from the top surface of the bottom slab). The thickness of the foundation slab is 40 cm, and the thickness of the external walls is 30 cm. Tank walls were reinforced with Ø14 mm mesh every 30 cm in the parallel and meridional directions, which in combination with the foundation slab, was condensed (Ø14 mm every 15 cm).

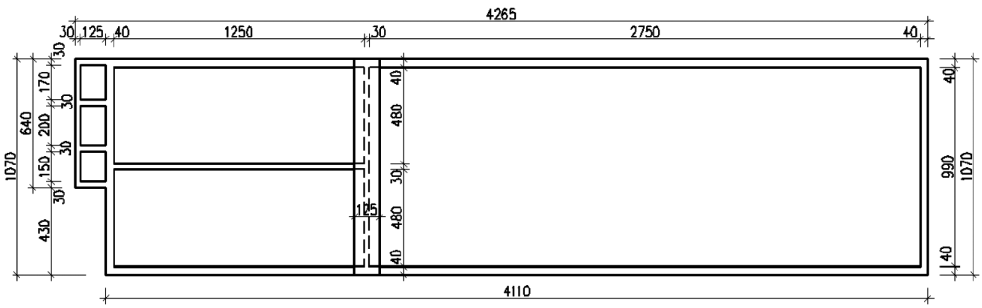

Fig. 8. Tank diagram – tank projection from the top (4)

The main reason for the tank to fail was the adoption of simplified static diagrams, the omission of the axial forces occurring in the walls, and the omission of temperature effects. The cumulative effect of the errors was that the actual work of the tank structure was not modelled.

5. Differences in the results of two- and three-dimensional analyses based on the example of the football stadium model

The examples given in the section below clearly show what errors can result from oversimplifications of a model. The results of the two-dimensional analysis were compared with those obtained from a three-dimensional model. The discussed object is a football stadium, the numerical analysis of which was performed in the SOFiSTiK environment.

5.1. The boundary conditions adopted

For simple structures, a virtual cut-out of an individual structural element (e.g. a beam) and assignment of boundary conditions consistent with the classical mechanics, i.e. fixed or hinged, in general, does not lead to significant errors.

For complex spatial structures, however, verification of the actual support conditions plays a very important role since the nature of the element's work is no longer so obvious.

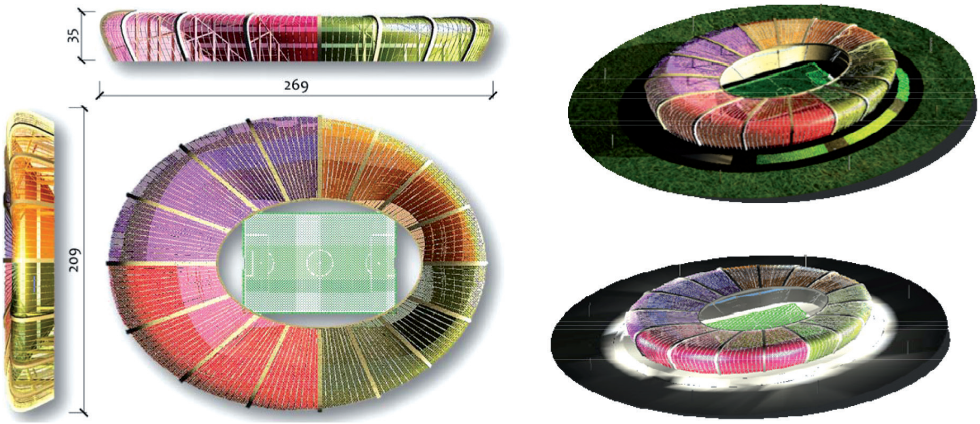

Fig. 9. Size of football stadium and its visualisation (done by the authors)

Below an example of a two-span beam as a binding joist of the third floor of the stadium is given.

In different models, the functions of bending moments, resulting solely from the dead weight of the entire structural system, were analysed. For one-dimensional models, it is impossible to determine the impact of the remaining part of the structure on the beam. This is because spans are not directly loaded, and the interaction between components is transmitted through the nodes. Numerical analysis of the question leads to interesting conclusions.

Fig. 10. Models of the beam support: hinged, fixed, monolithic in 2D frame, monolithic in 3D skeleton arrangement

The 2D frame model changed the nature of the supports at the beam-ends due to different levels of stiffness of the elements connected in the node. The first support behaves in a similar way to the hinge; the second one is similar to the fixed support. However, the respective moment is over 30% greater than the fixing moment of the one-dimensional analysis. Such a result, without taking into account the impact of deformation, would not be possible. In the 3D model, the moments changed not only quantitatively, but also qualitatively – stretching of lower fibres occurred in the first node. The omission of this fact in the calculation is, of course, unacceptable. In addition, over the centre support the value of the bending moment increased by over 35% compared with the 2D analysis and up to 70% compared with the 1D analysis with the supports.

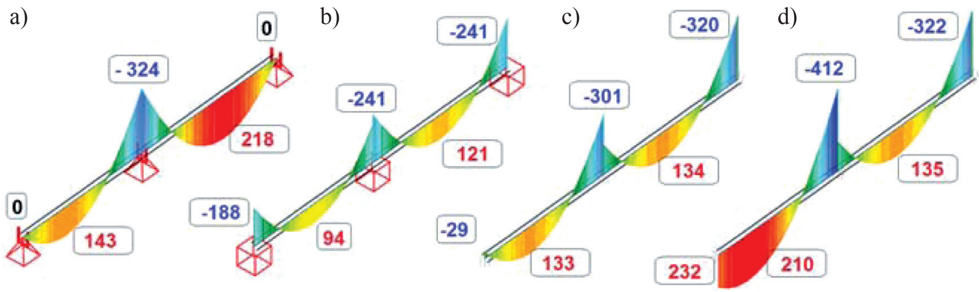

Fig. 11. Bending moments (kNm) for different support conditions: (a) hinged (b) fixed (c) monolithic in the 2D frame (d) monolithic in the 3D skeleton arrangement

This brief analysis leads to a simple conclusion – classic simplifications for complex engineering systems may lead to a qualitatively incorrect assessment of the structural response.

5.2. Work of a structure as a shell

The next issue is the bending analysis of the structure of the stadium with respect to the nature of roofing work as a shell. In the presented object, the elements can have spans of several dozen metres only when the interactions between the spatial girders, ring, and shell have been taken into account.

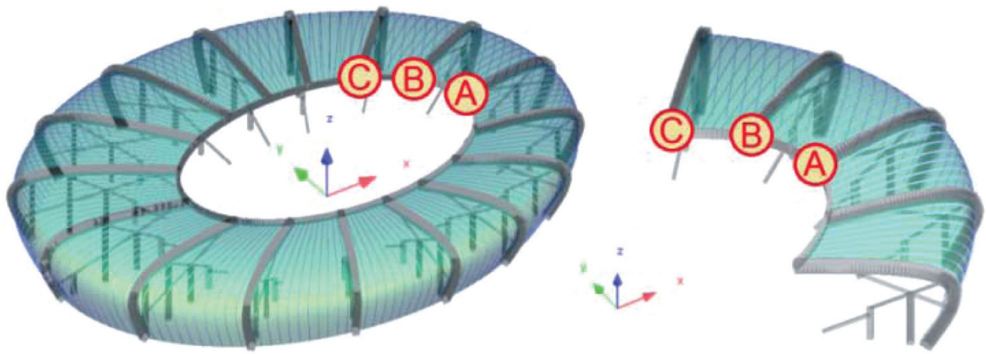

Fig. 12. Three-dimensional model of the total shell and of a part of it

Of course, it is possible to cut out a single 2D frame from the structure, or even an entire section of the structure (as in the figure above) and calculate the displacements using the program. However, such an approach wrongly assumes that girders are operating as cantilevers. In fact, the structure under dead load and other loads, works as a shell ribbed in two directions. The deflections are affected by the stiffness of the roofing structure in the longitudinal direction (perpendicular to the girders axis). To render this phenomenon as close as possible to the actual response of the structure, a three-dimensional model needs to be used. In our case, even a simplified model (peripheral stiffness ensured only by the shell) showed that the actual deflections are reduced by about 20% from those obtained with the support model.

Table 1

Deflections for the discussed models calculated using the SOFiSTiK (mm) program

point	direction	deflections in the complete configuration	deflections in the fragmentary configuration	change %
A	z	–87	–102	17.2
B	z	–102	–118	15.7
C	z	–92	–114	23.9

5.3. Two- or the three-dimensional space

To perform a 2D analysis, the engineer must have greater experience and intuition because it is essential to adopt certain assumptions. When discussing the frame, the question of the connection of the girder with the compressed circumferential ring arises. From among many possibilities, partial fixing was adopted, which allows a vertical displacement, but at the same time induces bending moments. Loading with a shell (the steel truss) was assumed to be as evenly distributed over the girder length, and the weight of the ring was modelled by a concentrated force. In case of the 3D model, simplifying assumptions described above were not made.

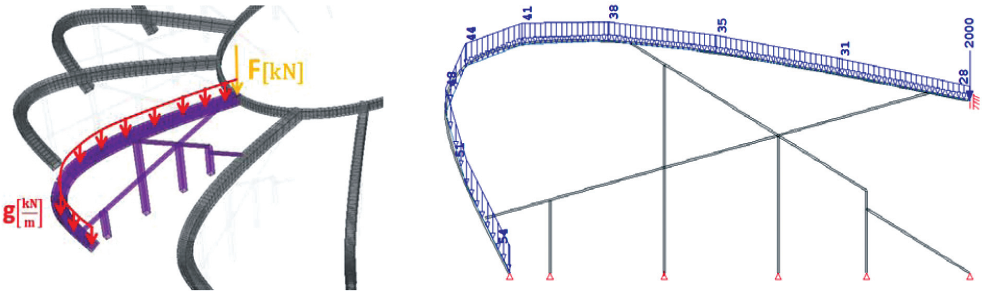

Fig. 13. Static 2D frame diagram

Numerical analysis results showed over-dimensioning of the structure's elements in 2D analysis, i.e. the values obtained for the cross-sectional forces of the presented example are on average 20% higher in the 2D than in the 3D model. This is due to the fact that the three-dimensional object has a spatial stiffness, which is not available when 2D frames are chosen for modelling.

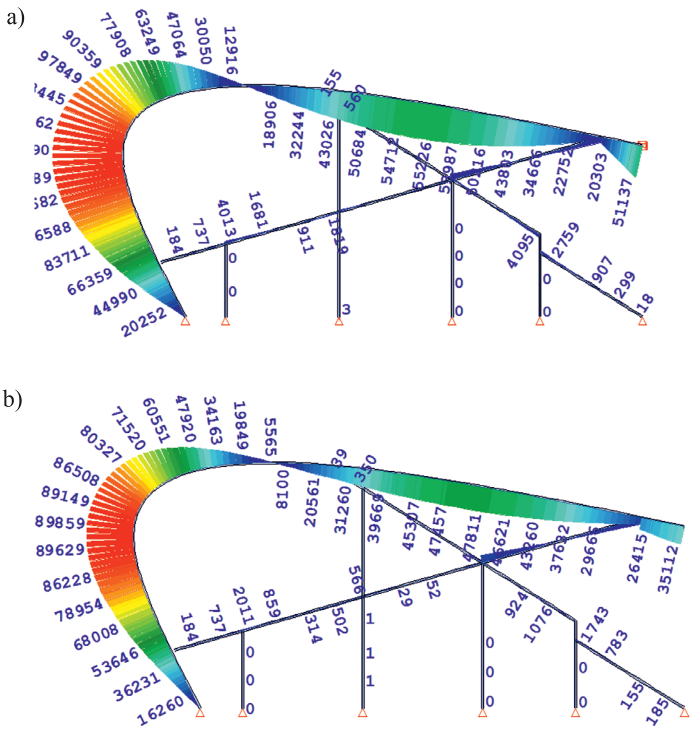

Fig. 14. Bending moments (kNm): a) from 2D analysis; b) from 3D analysis

5.4. The rod or shell model

The awareness of the need for the 3D design of building facilities has become increasingly common, which is proved by an increasing number of programs to model structures in such environments. In some cases, applying models that involve only spatial features of the geometry of objects is not enough. It is often necessary to replace rod models with the solid or shell models. Such analyses are most frequently performed for nodes and points of application of major concentrated loads. To illustrate the problem, simple diagrams present the results obtained from the solution of two models – rod and shell models. The effects of the two models as deformations are shown in the same scale.

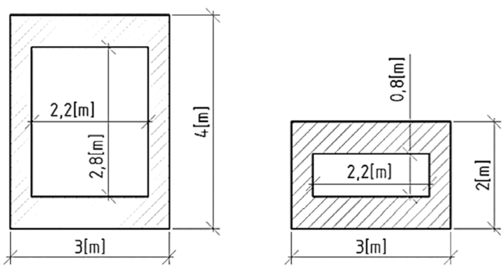

Fig. 15. Cross-section of the girders at the base and at the top

The analysis of the shell model showed that in the connection area, there is a stress state in the girder which cannot be determined on the rod model.

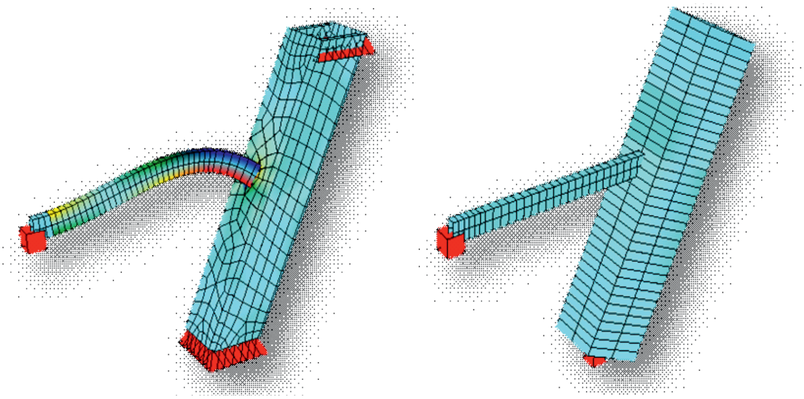

Fig. 15. On the left: the shell model of the girder; on the right: the rod model of the girder

6. Conclusions

The article presents examples of errors made in the assessment of a structure's work. These errors, resulting from the adoption of an incorrect model, show how important it is to realistically model the actual behaviour of structures. The complexity of the facilities designed nowadays very often makes the adoption of simple models that involve a number of simplifying assumptions which are inadequate. This may effect in incorrect quantitatively, and sometimes also qualitatively, assessment of the structure's work. Creating structural models requires the designer's significant experience and a proper understanding of the performance of a structure. Unfortunately, even the most complex three-dimensional model, if based on incorrect assumptions, will result in an incorrect structural solution.

In the article, only elastic models of structures were analysed, models taking into account other physical laws, crack formation in reinforced concrete structures, or concrete creep omitted deliberately. Taking into account these material properties would render an unambiguous assessment of the errors resulting from specific models difficult.

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