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# DURABILITY OF FLEXIBLE CORRUGATED STEEL SHELL STRUCTURES - THEORY AND PRACTICE[1]

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The technical issues described in this paper concern the durability aspects of buried flexible steel structures. It is well known that due to the nature of the bridge loads including buried flexible steel structures, they are particularly exposed to fatigue. Fatigue of steel structures – in this case corrugated steel plates - is closely related to such important parameters as safety and durability, and has direct impact on the service life of these structures. As these issues are very important, they are often analyzed by many research centers, with the present author contributing to the work of many of them. Fatigue reveals itself in the critical phase as fatigue cracks in structural steel, or in the joints. In such critical cases this leads to the exclusion of objects from the service. The fatigue of soil structure around the steel corrugated shell in the structures under analysis should also be taken into account.

Fatigue in steel structures intensified by the occurrence of corrosion due to the operating conditions of the structures (negative environmental impact of water) is widespread.

According to the author, proper construction of buried flexible steel structures and their maintenance undoubtedly increase the safety of users and extend the service life.

At the end on the paper the author describes one of the methods of increasing the durability of shell structures by reinforcing the soil using a geotextile geomembrane.

Key words: flexible steel structures, durability, fatigue, corrosion, service life.

## 1. INTRODUCTION

Significant technical progress in the construction, materials and the range of spans and structural dimensions of corrugated steel structures was recorded in recent years. Poland is one of the leaders in the construction of such structures, including also eco-bridges, currently built in Poland. As is generally known the main advantage of modern construction of culverts is the cooperation of corru-

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gated shell with the soil to carry service loads. Given the ever-growing transport needs, a very important aspect is the service life of these structures. Therefore, their technical condition and the way in which they are maintained are extremely important.

## 2. DETERMINANTS OF THE DURABILITY OF CORRUGATED STEEL SHELL STRUCTURES

### 2.1. Reserves of bearing capacity from the calculation methods applied in the design

Many random parameters must be taken into account in the design of the corrugated steel soil-shell structure, occurring mostly due to static and dynamic loads, and caused by service factors. The applied standards for modeling structures have a lot of imperfections and are constantly modified following developments in technology as well as following continuous electronic monitoring of the existing structures.

Culvert design methods change also with the development of science and technology in engineering design. The commonly used analytical calculation methods are generally based on the experiences of designers and also on the "work" of these structures in natural conditions. This is due to the difficulties associated with the actual reflection of the behavior of the structure in practice. In the analysis it is necessary to take into account a number of factors, including the interaction between the shell structure and the surrounding soil. Due to the complexity of these issues, their analysis requires the use of advanced numeric calculations. Development of computer analysis methods, based on the FEM finite element method, has been implemented in recent years also to calculate the construction of soil-shell culverts, and more recently – animal passages. FEM takes into account a wide range of relevant parameters, which cannot be analyzed by analytical methods. For this reason, it better reproduces the reality, especially in the analysis of the various phases of operation, which was confirmed by the results of many tests, e.g. those conducted by the present author in natural conditions. For this reason in the author's opinion FEM will be increasingly used to calculate soil-shell structures, despite some difficulties and the effort required to apply them. It should be noted that creation of a computational model has the greatest impact on the results of the calculations. The difficulty of calculating these structures using the finite element method is graphically shown in Figure 1 [9].

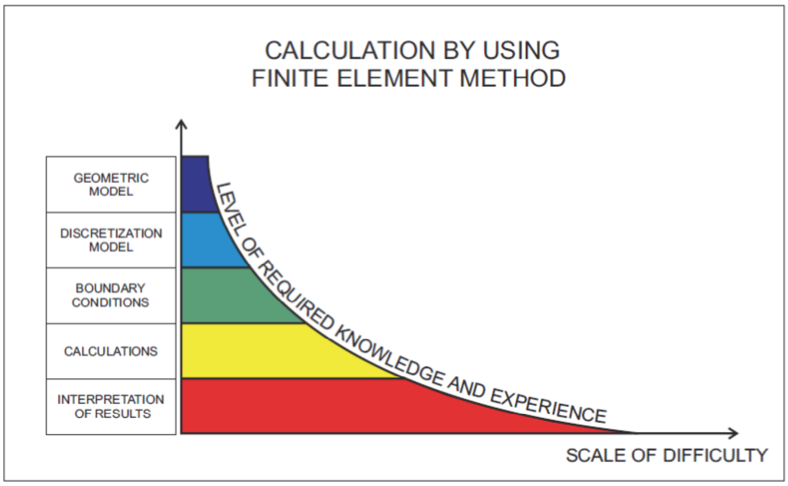


Fig. 1. The level of difficulty of using FEM to calculate soil-shell structures. [9]

It should be noted that despite the development of numerical methods, analytical methods are still widely used by practitioners. Numerical methods have become popular following the advancement of computational models, while analytical methods must take into account the limitations of safety factors, which must always be considered.

### 2.2. Types of corrugated steel shell structures and their anticorrosive protection

As is generally known, shell structures with the steel corrugated sheets are produced in a wide range of cross-section types (amplitude of corrugation) [3], [6]. The amount of the cross-section is selected by the designer based on the analysis of stiffness, depending on the effects of the structure. During service life various parameters which characterize the corrugation of profiles must be considered, among them the moment of inertia - I and the modulus of strength – W. Materials and technology for the construction of these structures are modified continuously. One of the ways to improve capacity, as well as increase the span is to modify steel sheet corrugation. The methods used include optimization of the height of steel corrugation. This upgrade involves, for example, the use of additional transverse corrugation which stiffens the steel structure in areas exposed to stress concentrations. Such structures can be found more often in Poland in new infrastructure facilities.

Results of full scale tests under the exploitation load have shown that with the conventional design of the sheet thickness (5.0 – 7.5 mm), the stresses in the steel plates are less than 30.0% of their theoretical capacity. Therefore the sheet thicknesses in these structures can be continuously optimized while maintaining the required safety factors.

In the case of soil-shell structures the corrugated sheet at the proper performance of the backfill with suitable mineral material has the optimal durability of anti-corrosion of steel. Generally, zinc coating is the most durable protection of steel surfaces, mainly due to the formation of the permanent bond of the galvanizing zinc coating of the steel surface, which forms an alloyed layer. Other protection methods are based on the use of bonding the coating to the substrate by a physical adhesion effect. A zinc coating applied by immersion is a generally effective corrosion protection for this type of structure. The durability of non-painted coatings containing zinc and aluminum (Zn-Al) is approx. 50% higher than the durability of zinc coatings, because of the higher corrosion resistance. The Duplex system can be used to improve the durability of structures, i.e. zinc coating can be covered with additional paint layers. The durability of such systems is usually greater than the sum of both the protection period and the coating given by equation 2.1 [8]:

$$S_{Du} = 1{,}2 \div 2{,}5\ (S_{Zn} + S_{Coat.}) \tag{2.1}$$

where:

$S_{DU}$ – the period of protection (durability) – Duplex system,
$S_{Zn}$ – the period of protection (durability) – zinc or aluminum-zinc,
$S_{Coat}$ – protection period (durability) – paint coating.

Despite this kind of steel sheet protection, from the point of view of durability it is the lower part that is most exposed to abrasion. This is particularly the location of objects in the foothills and mountainous areas with increased speed of water flow, often with sand and rocks. It has to be noticed also that galvanizing is not an effective method of anticorrosion protection against low pH soil or groundwater.

Today, Trenchcoat™ polymer protective coating is used for better corrosion resistance in highly aggressive environments. This coating significantly increases corrosion protection and combines the advantages of galvanized sheet steel with the chemical resistance of polymers (Fig. 2). Please note that the anticorrosive protection structures of steel corrugated sheets should be effective throughout the life of the structures. They should be inspected regularly (according to applicable laws) and in case of damage or destruction of an additional protective coating or metal they should be repaired, again according to applicable regulations. It should be noted that as long as an additional protective coating is effective the service life of the structure is not in danger. An example of local corrosion of the corrugated steel surface in the area of the support on the reinforced concrete foundation is shown in Fig. 3.

Fig. 2. An example of two types of corrosion protection used in the construction of corrugated steel shell structures with the – zinc (on the left) and Trenchcoat polymer coating (on the right)

Fig. 3. An example of the local surface corrosion of corrugated steel shell structure in the bottom area (example from South Argentina)

### 2.3. The type of soil backfill assumed in the technical design

Given the stability of these objects not only the durability of the basic steel shell structure but also the soil backfill must be taken into account,. Backfill should have very good parameters because they have a direct impact on the proper "work" of this type of structure in transferring service loads [2], [3], [7]. With proper density, the soil should not reduce its volume under operating loads (including multiple and dynamic loads), characterized by a high internal friction and a lack of cohesion. It should be noted here that in the event of intensive vibrations, dynamics, or the load from all type of vehicles, there may be a total lack of internal friction in the center of the backfill, which is characterized by the properties of viscous liquid. Therefore, soil is particularly preferred due to its large percolation. When selecting the optimal material for backfill the aggregate gradation must be taken into account, which should be chosen depending on the size of the corrugation of steel structure [8], [10]. For the optimum strength parameters, and thus the durability, the backfill material should be laid in layers and then consolidated. The system must be done symmetrically and fill the height at the same time on both sides of the structure of the shell, and all layers should have the same height. Before another layer is placed, the previous one must be properly consolidated. Recently, lightweight construction aggregates are also used in engineering practice as backfill. This is particularly advantageous when building high embankments (high over-layer of structure) or in weak soil conditions. Those aggregates are characterized by good strength properties and can be an alternative to natural aggregates. In addition, according to PN-EN 1997-1 when selecting the backfill material an aggregate of artificial origin can also be taken into account. In this case, however, after laying the backfill the possibility of laying local cementing aggregate should be considered.

## 2.4. The depth of soil cover over the shell structure

According to current recommendations [11] the minimum depth of cover for all structures made of corrugated sheet except for the frame structures, is determined in equation 2.2 as follows:

$$H = \frac{S_i}{8} + 0{,}2 \quad [m] \quad \text{or} \quad H = \frac{S_i}{6} \quad [m] \tag{2.2}$$

After calculation the value should not be less than 0.60 m - for road and rail traffic loads. For all types of structures it is possible to reduce the amount of cover depth , while the use of reinforced concrete relieving slab or reinforcement geogrid is possible (tests of such structure are described in Section 3 of the paper). The depth of cover of the structure is fully dependent on the aggregate quality used and construction conditions. The author of the paper repeatedly encountered failures of these structures associated with the loosening of soil layers of the cover of the shell structure. Temporary facilities completed to serve the needs of the construction site are particularly affected, since they do not have a permanent road pavement over the structure.

The reason for the failure in question is shown in Figure 4a and an example of the failure is shown in Figure 4b.


Figure 4a. Example of damaged steel shell structure built as culvert within highway during its construction

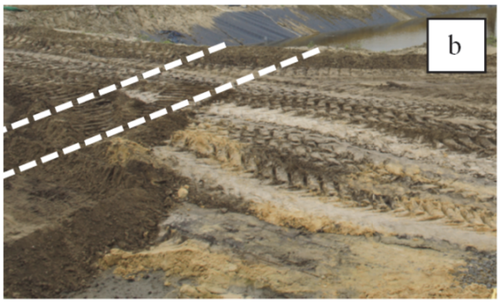


Fig. 4b. Visible inappropriate conditions of soil backfill over the structure (cohesive soil, too low thickness of backfill with intensive construction-site traffic

## 2.5. Proper drainage

As the author mentioned at the beginning of the paper, the technological progress in the construction of bridges, eco-bridges as soil-shell structures is significant. This applies to the calculation methods, materials, larger spans, and the number of structures actually built. Despite the undeniable advantages of this type of structure, which the author mentioned many times in, e.g. [12], [13], [14], [15], [16], since these solutions were often implemented very quickly, problems related with, e.g. proper drainage, have not always been taken into account. They have a direct relationship with the bearing capacity, durability and maintenance of these facilities [5], [17], [18]. Such a state of affairs is confirmed by the results of inspections carried out on these structures from the beginning of their introduction to engineering practice as well as those recently completed. This condition is illustrated by photographs presented in Figures 5 and 6. This applies to both the surfaces of these objects as well as the observed leakage by the support area.

Fig. 5. Example of hollows of water on the soil surface of the eco-bridge situated above the main railway line and expressway

Fig. 6. Example of leakage on the front wall around the middle support area of an eco-bridge

## 2.6. Proper equipment of culverts and passages for animals

Sufficient durability of flexible corrugated steel shell structures depends also on elements of its equipment. The essential elements affecting the durability of these facilities, as a whole, are in particular the heads, slopes, as well as adequate protection of the watercourse [9]. An example of an inappropriate way to secure the slope of a flexible shell structure is shown in Figure 7. An example of the right solution of strengthening the watercourse of culverts is shown in Fig. 8.

Fig. 7. Example of improper protection of slopes using geotextile in corrugated soil-shell structure in service

Fig. 8. Example of a proper solution strengthening the watercourse using stone material and turf

Additionally, elements of equipment should be chosen so that the assumed intended working life operation of the facility is efficient and provides appropriate usability (in the case of passages for animals they are e.g. shelves for animals mounted inside the structure with the corrugated sheet). Examples of imperfections in the shelves for animals in the soil-shell structures are shown in Figures 9 and 10.

Fig. 9. Example of shelves for animals in a complex functional culvert. An erosion of soil surface on the shelf and the corrosion of the shelf structure can be seen

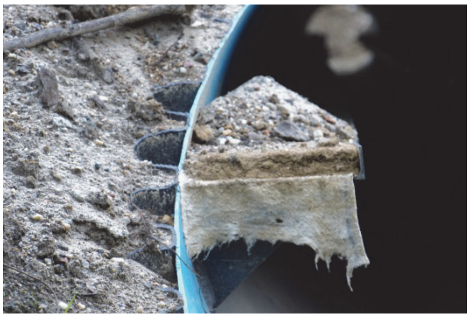

Fig. 10. Example of shelves for animals with inadequate width. Damage of the geotextile reinforcement of its surface

### 2.7. Method of construction

As is generally known, flexible corrugated steel shell structures need special attention during their construction. This applies to both high technological regime, as well as the quality of construction works - especially in the early stages. The quality of the backfill, built at the early stage, has a big impact on the durability of the entire facility [11]. This is particularly important in the case of structures of circular and arched cross-sections. These types of structures are characterized by high susceptibility to horizontal deformation – in the case of unsymmetrical laying and consolidation of backfill, and vertical deformation – in a situation when the backfill is put symmetrically on both sides of the structure. Therefore, during the laying and compaction of backfill the deformation the shell should be continuously monitored.

Especially dangerous is the response of the shell on the side soil pressure of the backfill. A thin structure made without backfill does not have an adequate load capacity [1]. And this phase of the construction, i.e. laying and compacting the backfill, is the biggest problem with these types of structures. This is due to the possibility of many forms of buckling and loss of stability. As engineering practice shows, the effects of the lack of adequate quality of the construction works during backfilling are not noticeable immediately, but after a few month or even a few years of service. They manifest themselves in local deformation of the grade line of the road as a result of soil consolidation in the area of shell structure. Examples of inappropriate practices of backfilling flexible corrugated steel shell structures are shown in Figures 11 and 12.

Fig. 11. Example of the initial stage of backfilling of a flexible corrugated steel culvert structure. An inadequate size of backfill in the side zone of the structure can be seen

Fig. 12. Example of backfilling of a flexible corrugated steel culvert. An unbalanced embankment resulting from horizontal deformation of the steel shell structure can be seen

### 2.8. The phenomenon of fatigue in steel soil-shell structures

During the service of steel structures, specific cracks often appear in their structural elements under the impact of multiple cyclic loads that cause stresses even much smaller than the maximum durability of the material. This phenomenon is called fatigue, and the final effect of this phenomenon - fatigue destruction.

Fatigue is reflected adversely on the work of the structure, as it restricts to a greater or smaller extent its durability, and in many cases leads to dangerous failure. There are many known examples of structural disasters caused by fatigue cracks; they all entailed serious economic losses.

In the case of steel soil-shell structures, the fatigue phenomenon must also be taken into account. Displacement of the steel shell structure during operation also causes concentration of local stresses in steel sheets. These displacements are mainly observed in the case of railway structures with a small soil cover. This is because of the effects of cyclic large horizontal forces on soil-shell structures during rollover of rail vehicle. This is particularly important when a rail vehicle has to perform emergency braking on these structures, where the horizontal forces reach their maximum value. In the authors' opinion the phenomenon of fatigue in the case of these structures is a long-term phenomenon, but should be taken into account when calculations for the existing steel soil-shell structures are made.

## 3. INCREASING DURABILITY OF FLEXIBLE CORRUGATED SHELL STRUCTURES – A TEST SOLUTION

As already mentioned in the paper, there are several proven technical solutions to increase the capacity of flexible corrugated steel shell structures. These solutions are increasingly being used when the cover over the shell structure is low. This is because of the existing conditions of the terrain where there is no technical and economic possibility to raise the road or railway embankment. For this purpose additional structural elements could be built into the layer of soil cover over the shell structure. It can be either widely used massive reinforced concrete slabs or as well as the more and more appropriate solutions based on the use of geotextiles and geogrid. Considering the economy, according to the author the use of geotextiles, as an element increasing the capacity of flexible corrugated steel shell structures is most reasonable. This was also confirmed in the tests of such structures performed under the guidance of the author. Figure 13 shows an example of the use of geotextile reinforcement of road flexible corrugated steel culvert with the low soil over-layer.

Fig. 13. Example of additional reinforcement of flexible corrugated steel shell structures with geotextile built in the upper zone of backfill.

### 3.1. Description of the tests

A natural scale model of the flexible corrugated steel box-section shell structure (Boxculvert type) was tested. The testing was carried out on the test model in the Research Institute of Roads and Bridges in Żmigród. The aim was, among others, to comprehensively analyze structures under static, dynamic and fatigue loads [19], [20]. The tests were performed on two models of structures without and with reinforcement in the form of single-layer of geogrid built in the upper zone of the backfill. This helped us to determine the effect of reinforcement on the recorded displacements and stresses in the shell structure. The research also included measurements of displacements and stresses during the construction of the model – including laying individual layers of backfill. The construction of a test model included all stages of culvert construction, built in accordance with current standards and regulations. In order to obtain reliable results necessary for further analysis properly installed measurement systems were used [11]. Figure 14 shows the schematic arrangement of sensors for the test structures of Box Culvert.

### 3.2. Test results

The stress values occurring on the arch crown of the shell structure of the tested culvert for three variants of static load is shown in Figure 15. This graph shows a comparison of stresses in the structure without reinforcement and with the use of reinforcement in the form of single-layer of geogrid.

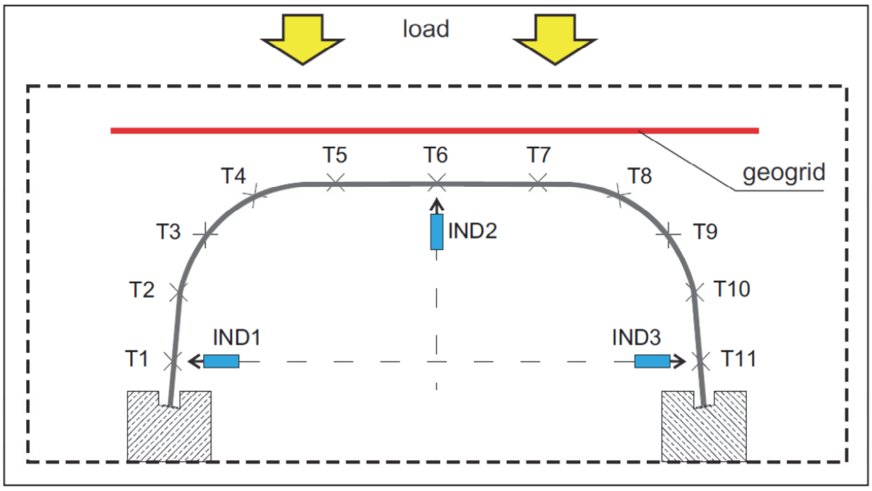


Fig. 14. Arrangement of strain and induction gauges for Box Culvert structures.

### 3.3. The increase of load capacity of flexible corrugated shell structure under testing loads

The tests clearly showed that the obtained values of stresses and displacements for steel shell structure are relatively small, even at loads far exceeding the standard loads. The study of two models of soil-shell structure (without reinforcement and with additional reinforcement in the form of geogrid) confirmed the positive effect of using reinforcement for the recorded displacements and stresses in the steel shell. The applied reinforcement helps to optimally distribute loads on the structure and at the same time increases the modulus of soil stiffness, which directly affects the load capacity of the entire soil shell structure.

Figure 16 shows the vertical displacement in the arch crown of the shell structure for both testing models.

**It must be noted that when reinforcement in the form of a geogrid was used, the loading capacity increased by approx. 30%.**

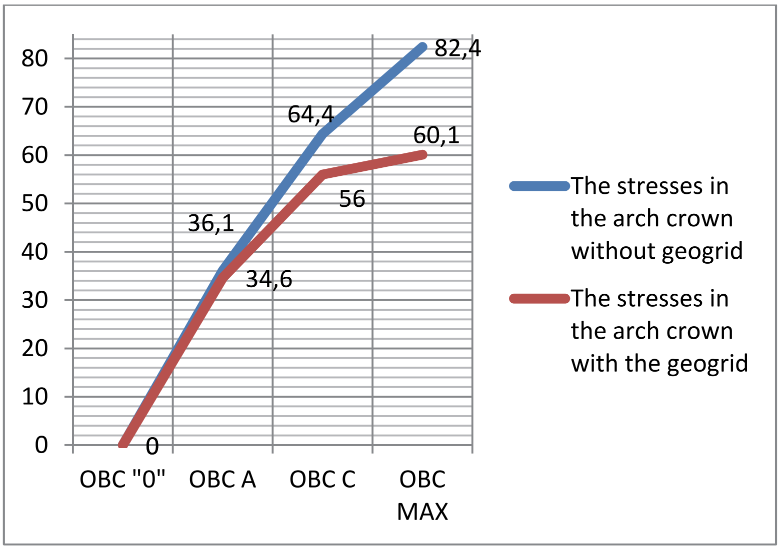


Fig. 15. The stress values occurring in the arch crown of the shell structure without reinforcement and with reinforcement in the form of a geogrid

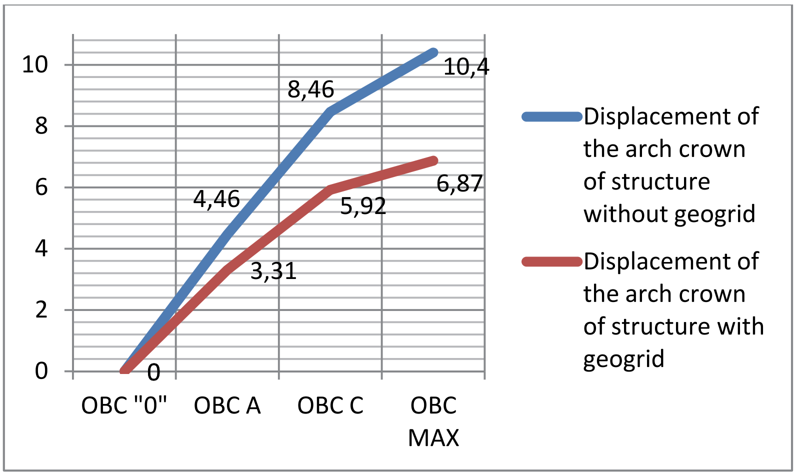


Fig. 16. Values of vertical displacement occurring in the arch crown of the shell structure without reinforcement and with reinforcement in the form of a geogrid

Figure 17 shows a comparison of the maximum stresses for both structures.

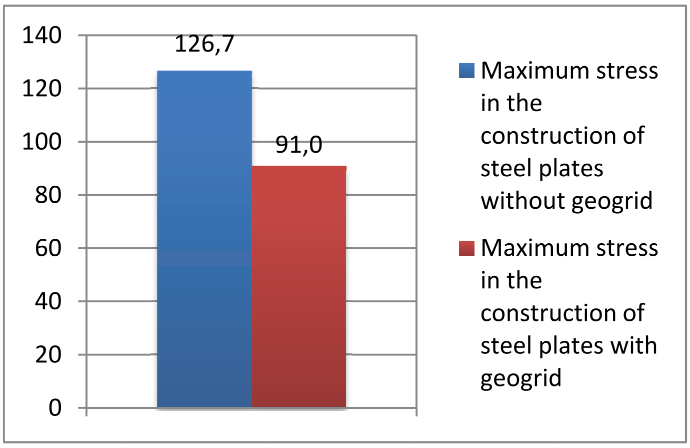


Fig. 17. Comparison of the maximum stresses for both structures

## 4. CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

1. On the basis of the experience gained during inspections of engineering structures conducted, among others, by the author of this paper, both in various European countries and in Poland, and the research and analyzes, it can be generally concluded that flexible structures with corrugated shells are durable and safe.
2. However, according to the author it is absolutely necessary to take into account the determinants of service life, which are briefly described in this paper. They are important for the bearing capacity and limit states of these structures. Not without significance is the effect of these determinants on the useful life of these structures during service.
3. Despite the fact that, as has been shown in the paper, the types of damage of this type of structures might not be irrelevant to their load capacity and, consequently, to their safety. However, individual elements will have to be continuously maintained, which increases operating costs. Not without significance is the impact on the deterioration of the aesthetic appearance of these facilities during their service.
4. According to the author the problem of proper drainage and anticorrosion protection requires special solution. It is very important nowadays, when the overall dimensions of culverts, ground-coating bridges, and extensive eco-bridges are being increased particularly from the point of view of their durability and maintenance

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