

## Application of Spatial Structures in Bridge Deck

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### Abstract

Spatial structure is a truss-like, lightweight and rigid structure with a regular geometric form. Usually from these structures is used in covering of long-span roofs. But these structures due to the lightness, ease and expedite of implementation are a suitable replacement for bridge deck. However steel and concrete is commonly used to build bridge deck, but heavy weight of steel and concrete decks and impossibility of making them as long-span bridge deck is caused engineers to think about new material that besides lightness and ease of implementation, provide an acceptable resistance against applied loads including both dead load and dynamic load caused by the passage of motor vehicles. Therefore, the purpose of this paper is design and analysis bridge deck that's made of double-layer spatial frames compared with steel and concrete deck. Then allowable deflections due to dead and live loads, weight of bridge in any model and also economic and environmental aspects of this idea is checked. As a result, it can be said that the use of spatial structures in bridge deck is lead to build bridge with long spans, reducing the material and consequently reducing the structural weight and economic savings. For geometric shape of the spatial structure bridge is used of Formian 2.0 software and for analysis of bridges is used of SAP2000 with finite element method (FEM).

*Keywords:* Spatial Structures, Bridge Deck, Steel and Concrete Deck, Finite Element Method, Deflection.

## 1. Introduction

In architecture and structural engineering, a spatial frame or spatial structure is a truss like, lightweight rigid structure constructed from interlocking struts in a geometric pattern. Spatial frames can be used to span large areas with few interior supports. Like the truss, a spatial frame is strong because of the inherent rigidity of the triangle, flexing loads are transmitted as tension and compression loads along the length of each strut. A spatial frame truss is a three-dimensional framework of members pinned at their ends. A tetrahedron shape is the simplest spatial truss, consisting of six members which meet at four joints. Large planar structures may be composed from tetrahedrons with common edges and they are also employed in the base structures of large free-standing power line pylons [1]. The simplest form of spatial frame is a horizontal slab of interlocking square pyramids and tetrahedron built from aluminum or tubular steel struts. Architects and engineers are always seeking new ways of solving the problem of spatial enclosure. With the industrialization and development of the modern world there is a demand for efficient and adaptable long-span structures. Spatial grid structures are a valuable tool for the architect or engineer in search for new forms, owing to their wide diversity and flexibility. Before entering into a discussion of the design and use of spatial grids in the late twentieth century, it is useful to look back at the early use of three-dimensional structures [2]. Until the middle of the eighteenth century the main construction materials available to architects and engineers were stone, wood and brick. Metals, being in relatively short supply, were used mainly for jointing of the other materials. Of the widely available materials, stone and brick are strong in compression but weak in tension. Thus they are suitable for three-dimensional structural forms such as domes and vaults. Impressive feats of vaulting were achieved by medieval masons but the largest span masonry domes, St Peter's Basilica in Rome (1588–93) and Santa Maria del Fiore in Florence (1420–34) are both approximately 42 m diameter at the base. Good quality timber has strength in tension and compression but is naturally available only in limited lengths and with limited cross-section [3]. For large-scale three-

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dimensional structures jointing of timber becomes a major problem. Nevertheless, the Todai-ji temple at Nara in Japan, the largest historic timber building in the world, is 57 m by 50 m and 47 m high. Although these materials were used to produce impressive large-scale structures, the spans were limited and the construction heavy. However, with the Industrial Revolution came the wider production of iron and then steel, high-strength materials that permitted the construction of more delicate structures of longer span or greater height [4]. At approximately the same time, mathematical techniques were being developed to describe and predict structural behavior and understanding of the strength of materials was advancing rapidly. Equally, with the advent of the Railway Age and the industrialization of commodity production come an increasing demand for longer span structures for bridges, stations, storage buildings and factories. With the wider availability of iron and steel and the demand for larger spans, there came a period of development of new structural forms, initially a multiplicity of different truss configurations and eventually three-dimensional spatial grids. Many structural forms including most spatial grid assemblies are modular. The concept and efficiency of modular building construction was dramatically illustrated, almost 150 years ago, by the design, fabrication and assembly of the metal framework of the Crystal Palace in Hyde Park, London, for the Great Exhibition of 1851 [5]. Landmark structures such as the Eiffel Tower in Paris constructed from wrought iron between 1897 and 1899, bear witness to the stability and durability of modular three-dimensional metal construction. The tower, built as a symbol for the centenary celebration of the French Revolution, and conceived as a temporary structure, has already survived over 100 years. Sadly, the magnificent 114 m span Galerie des Machines by Contamin and Dutert, built at the same time adjacent to the tower, has not. Such structures demonstrated the possibilities for the use of iron and steel in high-rise and long-span buildings and challenged the ingenuity of architects and engineers to discover new and more efficient ways for their construction. Probably the earliest examples of what we now commonly call spatial frames or spatial grids (light, strong, three-dimensional, mass-produced, modular structures) were developed by the inventor of the telephone, Alexander Graham Bell (1847–1922) [6]. In the first decade of the twentieth century he experimented with spatial trusses composed of octahedral and tetrahedral units. Despite Bell's development of lightweight three-dimensional spatial trusses early in the century, they were not used in architecture until the introduction of the MERO system, in 1943. This was the first spatial grid system widely available commercially and was developed in Germany by Mengerlinghausen (1903–88) [7]. Using what is still probably the most common method of spatial truss construction the system consists of individual tubular members connected at 'ball'-shaped node joints. The aesthetic appeal and popularity of this system has endured to the present day, as confirmed by the many alternative tube and ball systems now available. But the applications of spatial structures are not limited often used as roof for long-spans and three-dimensional spatial structures can be used to build the bridge deck with long-spans [8]. So in this paper, a double-layer spatial grid deck in which the node system is used compares with I-shaped steel bridges and concrete deck bridges in terms of span deflection, structural weight and economic and environmental aspects.

## 2. Modelling of Decks

For geometric shape of the spatial structure bridge is used of Formian 2.0 software and for analysis of bridges is used of SAP2000 with finite element method (FEM). For all models, including concrete, steel and spatial structure deck are carried out the linear static analysis. These models are consists of single-span bridge with total length 33 m and two-span bridge with length 33 m for each span. All decks are consists of two crossing line for passage of vehicles. Design of this bridges are according to the AASHTO (5th Edition, 2010) design standards (LRFD).

### 2.1. Steel Deck

Figures 1 and 2 show the examples of single-span and two-span bridges that consist of the I-shaped steel beams in combined with the concrete slab. According to figures 3, this deck consists of six beams and the total height of deck that including the steel beam and upper concrete slab (the steel-concrete composite slab) is about 223 cm.

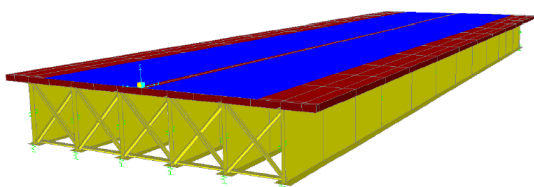


Figure 1. Single-Span Steel Deck

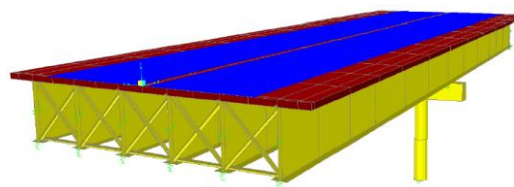


Figure 2. Two-Span Steel Deck

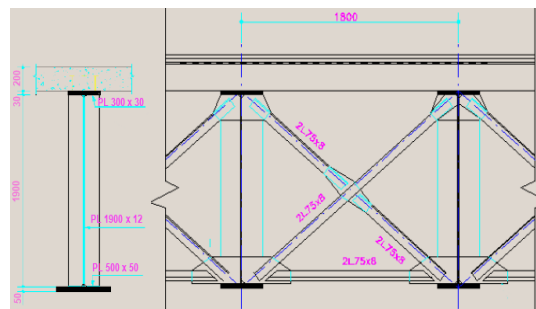


Figure 3. Executive Details of Steel Deck

### 2.2. Concrete Deck

Figures 4 and 5 show the examples of single-span and two-span concrete bridge consist of precast concrete beams. According to figure 6, the deck of this bridge is made of six concrete beams and total height of deck is equal to 220 cm in both cases.

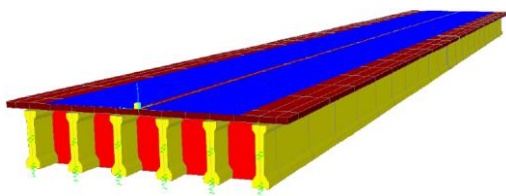


Figure 4. Single-Span Concrete Deck

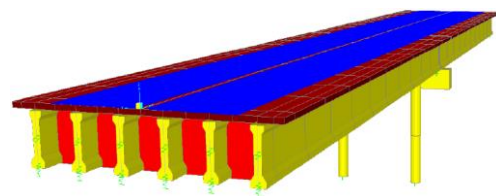


Figure 5. Two-Span Concrete Deck

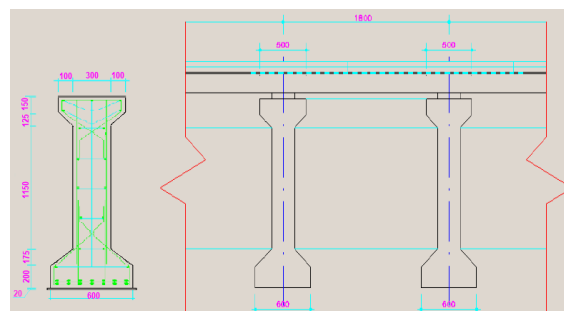


Figure 6. Executive Details of Concrete Deck

### 2.3. Spatial Structure Deck

Figures 7 and 8 show the examples of double-layer spatial grid bridge in case of single-span and two-span. Topology of these two-layer spatial grid deck is square on moved square and as seen in figure 9, the MERO system is intended for the connection between members. Because of the connections between members in the spatial grid deck is joint connections type, so there is no bending moment in the members and available forces in the members are axial forces [9]. It should be noted, the upper concrete slab is located on top layer nodes of the spatial grid deck and to prevent of bending moments development in the members, this concrete slab have no contact with the upper members of the double-layer spatial structure [10].

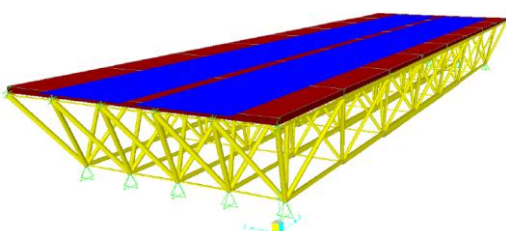


Figure 7. Single-Span Spatial Structure Deck

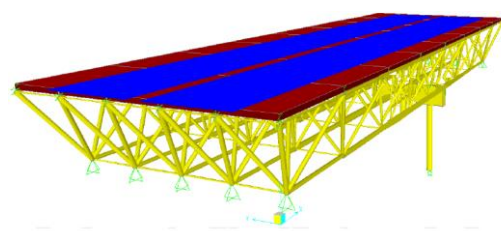
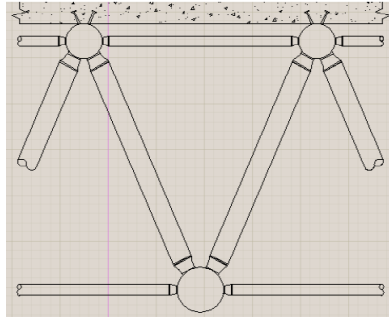


Figure 8. Two-Span Spatial Structure Deck



**Figure 9. Executive Details of Spatial Structure Deck**

## 2.4. Wearing Surface Dead Load

In the steel and concrete decks, dead load of wearing surface is applied to the concrete slab and is assumed to be equally distributed to each girder. A wearing surface with a thickness of 20 cm is assumed. In fact, dead load is due to concrete slab weight with thickness of 20 cm and weight of asphalt on it. According to equation (1), dead load of the wearing surface for each girder is equal to multiplying unit weight of concrete slab by thickness of slab and dividing by the number of girders gives the following:

$$\text{Wearing Surface Dead Load (for each girder)} = \frac{0.25 \times 2500}{6} = 104.17 \text{ kg/m}^2 \quad (1)$$

But in spatial structures decks, dead load of the wearing surface that consists of concrete slab weight is applied to the all nodes of structure and is assumed to be equally distributed to each node. In fact, no load is applied to the members and as a result, the bending moments in the members is zero. Hence, there are only the axial forces in the members. The studied spatial structure deck in this article have 48 nodes in top layer, so according to equation (2), dead load of wearing surface for each node is equal to multiplying unit weight of concrete slab by thickness of slab and dividing by the numbers of nodes gives the following:

$$\text{Wearing Surface Dead Load (for each node)} = \frac{0.25 \times 2500}{48} = 13.02 \text{ kg/m}^2 \quad (2)$$

## 2.5. Vehicular Live Loads

The AASHTO LRFD (5th Edition, 2010) Specifications consider live loads to consist of gravity loads, wheel load impact (dynamic load allowance), braking forces, centrifugal forces, and vehicular collision forces. Live loads are applied to the composite section. In positive bending regions, the composite section is comprised of the steel girder and the effective width of the concrete slab, which is converted into an equivalent area of steel by multiplying the width by the modular ratio between steel and concrete. In other words, a modular ratio of  $n$  is used for short-term loads where creep effects are not relevant. In negative bending regions the short-term composite section consists of the steel girder and the longitudinal reinforcing steel, except for live-load deflection and fatigue requirements in which the concrete deck may be considered in both negative and positive bending. The AASHTO LRFD (5th Edition, 2010) vehicular live loading is designated as the HL-93 loading and is a combination of the design truck or tandem plus the design lane load. The design truck is composed of an 35.58 KN lead axle spaced 4.27 m from the closer of two 142.34 KN rear axles, which have a variable axle spacing of 4.27 m to 9.14 m. The transverse spacing of the wheels is 1.83 m. The design truck occupies a 3.05 m lane width and is positioned within the design lane to produce the maximum force effects, but may be no closer than 61 cm from the edge of the design lane, except for in the design of the deck overhang. In fact, the vehicular live loads are considered as follows [11]:

- Load of truck (400 KN) three-axis with length 10m.
- Load of tank truck (900 KN) six-axis.
- Uniform loads about 15 KN/M on each crossing lane.
- Concentrated load about 160 KN on each crossing lane (In unsuitable position).

### 3. Numerical Explain and Discussion

According to the “Code of Practice for Skeletal Steel Space Structures of Iran (No.400)”, for spatial structures bridge, the allowable deflection for dead loads is equal to  $\frac{1}{240}$  of the bridges span length. According to equation (3), the dead load deflection must be under this amount [12].

$$\delta_{(dead)} \leq \frac{1}{240} L_{(span)} \tag{3}$$

And the allowable deflection for live loads is equal to  $\frac{1}{1000}$  of the bridge span length. According to equation (4), the live load deflection must be under this amount [12].

$$\delta_{(Live)} \leq \frac{1}{1000} L_{(span)} \tag{4}$$

#### 3.1. The Obtained Results for Single-Span Bridges

Figure 10 show the weight of double-layer spatial structures deck compared to the weight of steel and concrete decks in case of single-span. According to the obtained results, the weight of double-layer spatial grid deck is substantially less than weight of steel and concrete decks. In fact, the lightness of spatial structures is one of most important advantages of decks built with these structures compared to other structural systems [13].

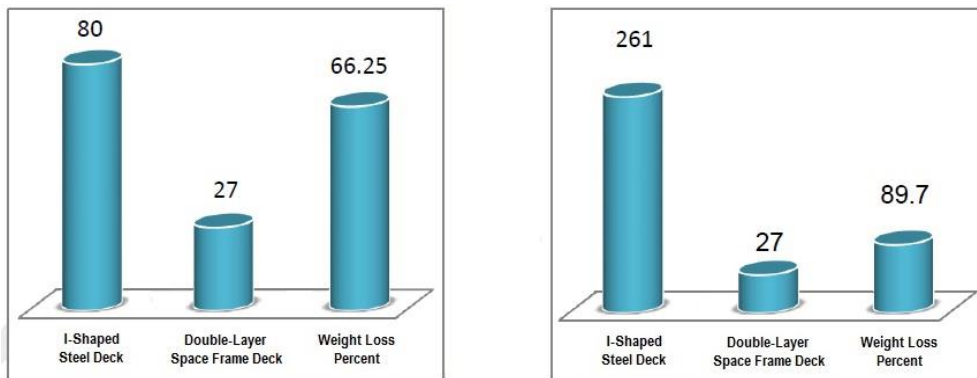


Figure 10. The Weight of Double-Layer Spatial Structure Deck Compared to Steel and Concrete Decks in Case of Single-Span (in %)

Figures 11, 12 and 13 show deformation and allowable deflection of the steel, concrete and spatial structure deck in case of single-span.

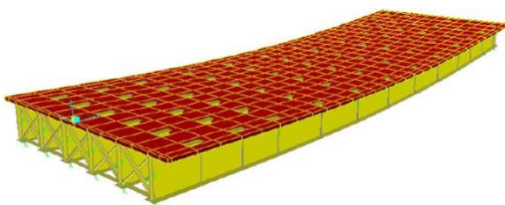


Figure 11. Deformation of Single-Span Steel Deck

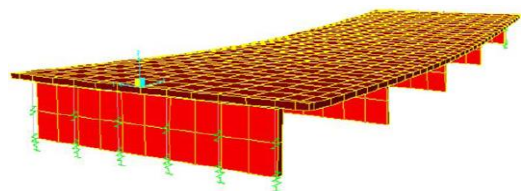


Figure 12. Deformation of Single-Span Concrete Deck

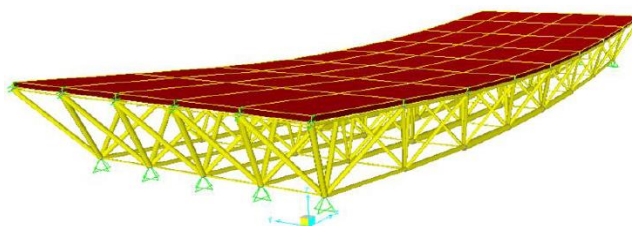


Figure 13. Deformation of Single-Span Spatial Structures Deck



Figure 14 show the structural and allowable deflection for the mentioned bridges. As seen, the structural deflection in double-layer spatial grid deck is more than steel and concrete decks. Because of the allowable deflection in the spatial structure deck is equal to  $\frac{1}{240}$  of span length for dead loads and  $\frac{1}{1000}$  of span length for live loads, hence, according to equations (5) and (6), the allowable deflection for the double-layer spatial grid deck with length of span 30 m is equal to 12.5 cm for dead loads and 3 cm for live loads. Since the structural deflection of this double-layer spatial grid deck is below of allowable deflection range, so this bridge is stable in terms of deflection due to dead and live loads. Increasing the structural deflection in the double-layer spatial grid deck compared of steel and concrete decks is due to use of joint connections in spatial grid deck and also the more rigidity of steel and concrete decks. Certainly in the double-layer spatial grid deck, the freely movement of elements is more than steel and concrete decks. Therefore the structural deflection is increased [14], [15].

$$\delta_{(Dead)} \leq \frac{1}{240} L_{(span)} = \frac{1}{240} \times 30 = 12.5 \text{ cm} \tag{5}$$

$$\delta_{(Live)} \leq \frac{1}{1000} L_{(span)} = \frac{1}{1000} \times 30 = 3 \text{ cm} \tag{6}$$

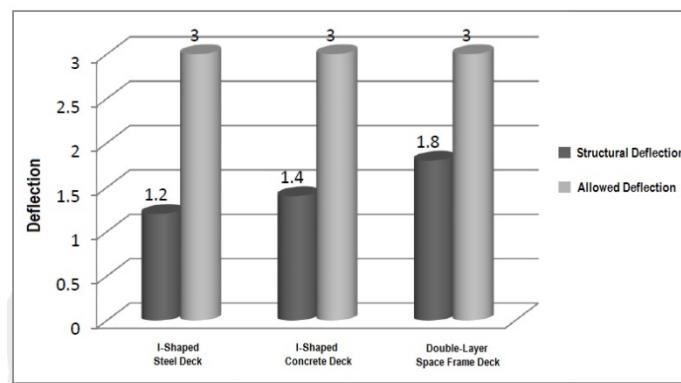


Figure 14. Structural and Allowable Deflections for the Steel, Concrete and Spatial Structures Decks in Case of Single-Span

### 3.2. The Obtained Results for Two-Span Bridges

Figure 15 show an estimate of deck weight percent that’s made of double-layer spatial structure compared to steel and concrete decks in case of single-span. According to this obtained results, the weight of double-layer spatial grid deck is substantially less than steel and concrete decks. Because of the spatial structures is lighter than another prevalent structural systems.

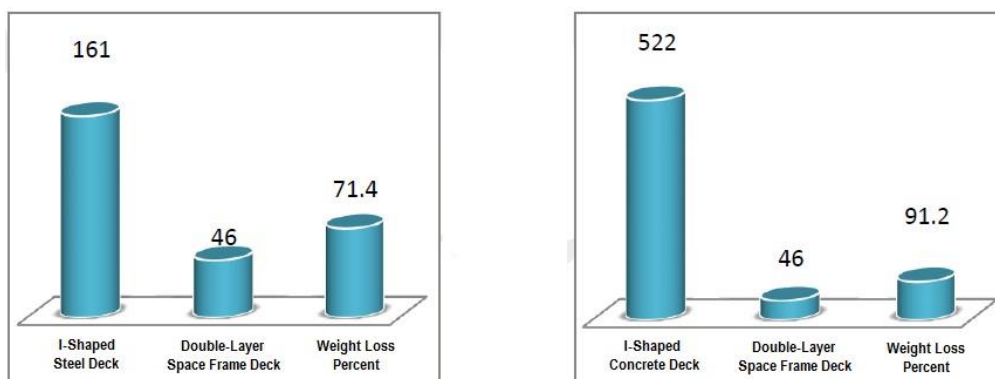


Figure 15. The Weight of Double-Layer Spatial Structure Deck Compared to Steel and Concrete Decks in Case of Two-Span (in %)

Figures 16, 17 and 18 show deformation and allowable deflection of the steel, concrete and spatial structure deck in case of two-span.

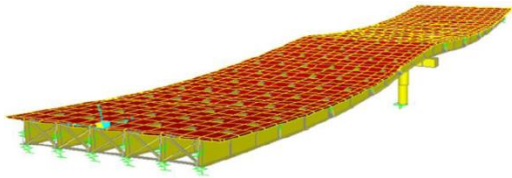


Figure 16. Deformation of Two-Span Steel Deck

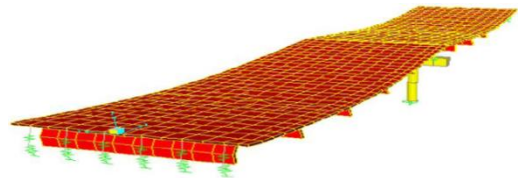


Figure 17. Deformation of Two-Span Concrete Deck

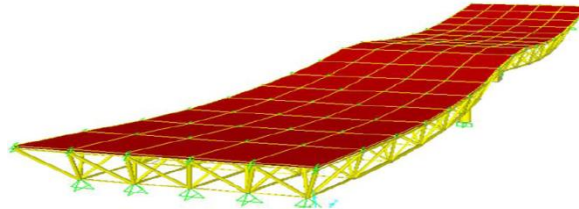


Figure 18. Deformation of Two-Span Spatial Structures Deck

As seen in figure 19, the structural deflection in double-layer spatial grid deck is more than steel and concrete decks. Because of the connections between members in the spatial grid deck is joint connections type, the structural deflection in double-layer spatial grid deck is more than steel and concrete decks. Because in double-layer spatial grid deck, the freely movement of elements is more than steel and concrete decks. Therefore the structural deflection is substantially increased. As seen, the structural deflection in the double-layer spatial grid deck is below of allowable deflection range, so this bridge is stable in terms of deflection due to live loads.

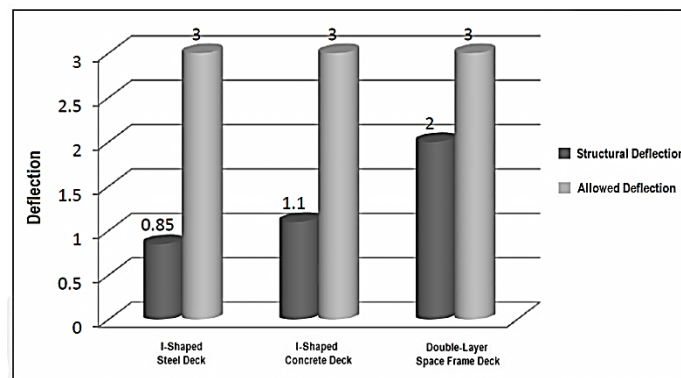


Figure 19. Structural and Allowable Deflections for the Steel, Concrete and Spatial Structures Decks in Case of Two-Span

## 4. Conclusions

Use of spatial structures in bridge deck is a better approach to build bridge with long spans, reducing material and consequently reducing structural weight and economic savings. Also use of these structures can lead to ease and expedite construction operations where need to build bridge (e.g. for the military purposes) in the shortest possible time. In other side, because the construction operations are done on the ground, so use of these structures in bridge deck is lead to decreasing dangers of work in height.

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