Solid Modeling and Finite Element Analysis of an Overhead Crane Bridge

C. Alkin, C. E. Imrak, H. Kocabas

The design of an overhead crane bridge with a double box girder has been investigated and a case study of a crane with 35 ton capacity and 13 m span length has been conducted. In the initial phase of the case study, conventional design calculations proposed by F. E. M Rules and DIN standards were performed to verify the stress and deflection levels. The crane design was modeled using both solids and surfaces. Finite element meshes with 4-node tetrahedral and 4-node quadrilateral shell elements were generated from the solid and shell models, respectively. After a comparison of the finite element analyses, the conventional calculations and performance of the existing crane, the analysis with quadratic shell elements was found to give the most realistic results. As a result of this study, a design optimization method for an overhead crane is proposed.

Keywords: overhead crane, finite element method, solid modeling, box girder.

Notation

b	distance between two side plates
b_k	width of lower plate
F_{AA}	static load due to the trolley
F_Y	load due to the working load
h_0	height of the girder end
h_2	height of the side plates
L_A	distance between trolley wheels
L_K	span of crane girder
L_P	distance between two adjacent supports
q	weight of one meter platform
q_K	weight of one meter maintenance platform
q_P	uniformly distributed mass units of bridge
t_1	thickness of the upper and lower plates
t_2	thickness of the side plates
x_2	distance between center of gravity and the midpoint of the left side plate
x_4	distance between center of gravitiy and the midpoint of the rail
y_1	distance between neutral axis and the midpoint of the rail
y_3	distance between center of gravity and the midpoint of the top plate
y_5	distance between neutral axis and the midpoint of the top plate
W_{X1}	moment of resistance on x-axis
W_{Y1}	moment of resistance on y-axis
γ_c	amplifying coefficient
ψ	dynamic coefficient

1 Introduction

Cranes are the best way of providing a heavy lifting facility covering virtually the whole area of a building. An overhead crane is the most important materials handling system for heavy goods. The primary task of the overhead crane is to handle and transfer heavy payloads from one position to another. Thus they are used in areas such as automobile plants and shipyards [1, 2]. Their design features vary widely according to their major operational specifications, such as: type of motion of the crane structure, weight and type of the load, location of the crane, geometric features and environmental conditions. Since the crane design procedures are highly standardized with these components, most effort and time are spent on interpreting and implementing the avaliable design standards [3].

There are many published studies on structural and component stresses, safety under static loading and dynamic behaviour of cranes [5–16]. Solid modeling of bridge structures and finite element analysis to find the displacements and stress values has been investigated by Demirsoy [17]. Solid modeling techniques applied for road bridge structures, and an analysis of these structures using the finite element method are provided in [18]. In this study, stress and displacements were found using FEM90 software. Solid modeling of a crane bridge, the loading at different points on the bridge and then application of the finite element method have been studied by Celiktas [19]. She presented the results of finite element methods for an overhead crane.

DIN-Taschenbuch and F. E. M. (Federation Européenne de la Manutention) Rules offer design methods and empirical approaches and equations that are based on previous design experience and widely accepted design procedures. DIN-Taschenbuch 44 and 185 are a collection of standards related to crane design. DIN norms generally state standard values of design parameters. F. E. M Rules are mainly an accepted collection of rules to guide crane designers. It includes criteria for deciding on the external loads to select crane components [3, 20].

In this study, the calculations apply the F. E. M. rules and DIN standards, which are used for box girder crane bridges. The calculation of the box girder uses the CESAN Inc. standard bridge tables. Then a solid model of the crane bridge is generated with the same dimensions as in the calculation results. Then static analysis is performed, using the Finite Element Method. Before starting the solution, the boundary conditions are applied as in practice.

2 Overhead cranes with a double box girder

Overhead travelling cranes with a double box girder not only hoist loads but also carry them horizontally. A double beam overhead crane is built of a trolley travelling on bridges,
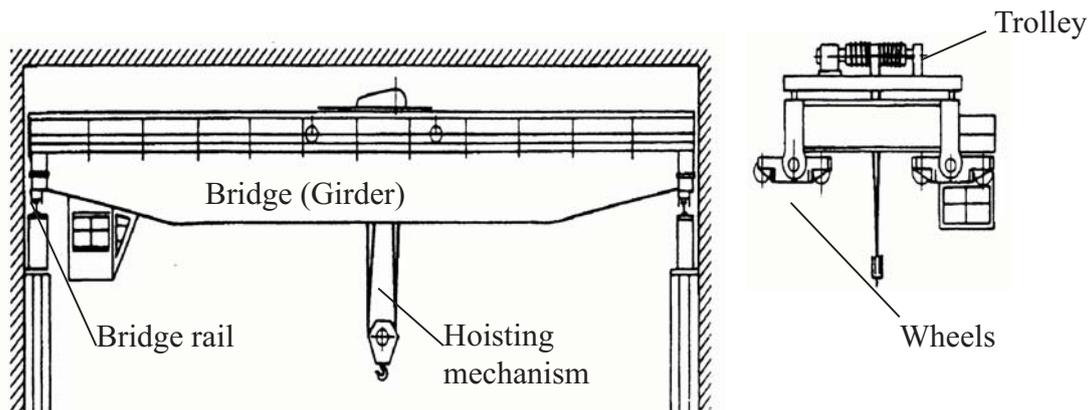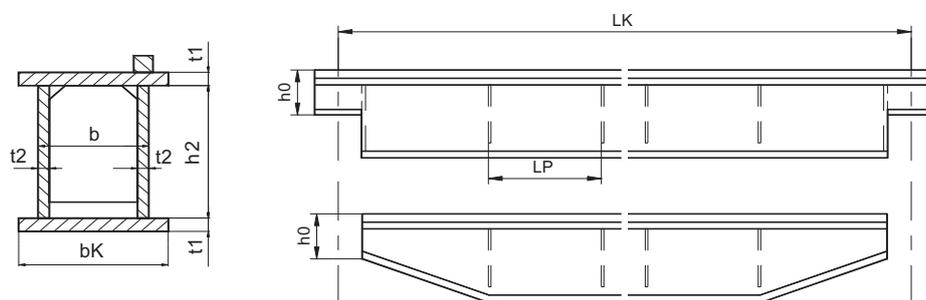
Fig. 1: Overall view of an overhead crane

Fig. 2: Construction requirements for a box girder bridge

and bridges travelling on rails. The trolley hoists or lowers the loads and carries them on the bridge structure. The bridges carry the loads on a rail. As a result, three perpendicular movements are performed. The system is depicted in Fig. 1, where the payload of the mass is attached to the bridge with wire ropes [21, 22].

The double box girders are subjected to vertical and horizontal loads by the weight of the crane, the working (hook) load and the dynamic loads. With a double box girder construction, the trolley runs above or between the girders. The acceptable construction requirements and values for a box girder bridge structure are shown in Fig. 2.

## 3 Application of FEM to an overhead crane

Among numerical techniques, the finite element method is widely used due to the availability of many user-friendly commercial softwares. The finite element method can analyse any geometry, and solves both stresses and displacements [23]. FEM approximates the solution of the entire domain under study as an assemblage of discrete finite elements interconnected at nodal points on the element boundaries. The approximate solution is formulated over each element matrix and thereafter assembled to obtain the stiffness matrix, and displacement and force vectors of the entire domain. In this study finite element modeling is carried out by means of the Cosmosworks and MSC commercial package. Patran and 4-node tetrahedral elements and 4-node quadrilateral shell elements have been used for modeling the overhead crane bridge.

The four-node tetrahedral element is the simplest three--dimensional element used in the analysis of solid mechanics problems such as bracket stress analysis. This element has four nodes, with each node having three translational and three rotational degrees of freedom on the x, y, and z-axes. A shell element may be defined, which allows in the plane or curved surface of the element and posseses both length. It width and may only be used in 3-D simulations. The four--node shell element is obtained by assembling the bending element to the appropriate degrees of freedom. This is sufficient as long as the shell element deflection is within the predefined ratio of shell thickness, otherwise the system works as a large deflection.

A typical four-node tetrahedral element and four-node quadratic shell element, and their coordinate systems are illustrated in Fig. 3 [24]. The four-node tetrahedral element chosen has six degrees of freedom at each node: translation in the nodal x, y, and z directions and rotations about the nodal x, y, and z directions. For the four-node quadratic shell element used to model the overhead crane girder, r and s denote the natural coordinates and δ is the thickness of the element.

This system does not have any horizontal force. The axial displacements and rotations of the first and last faces are equal to zero. In addition, the transverse displacement is zero at the first and last face nodes.

The external forces acting on the system are the mass of the main girder of the crane (distributed load) and the forces acting on the wheels of the trolley along the crane (active load). The forces acting on the trolley wheels are caused by the mass of the trolley, an the lifting load which will be moved on the crane.
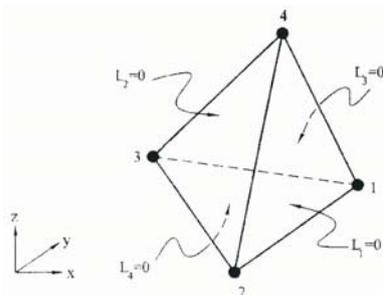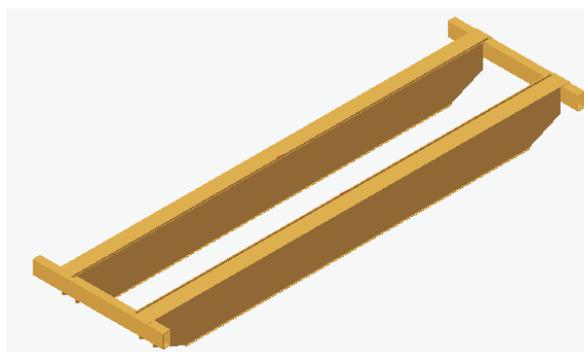
4-node tetrahedral element
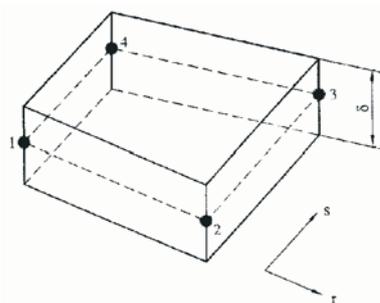
4-node quadratic shell element

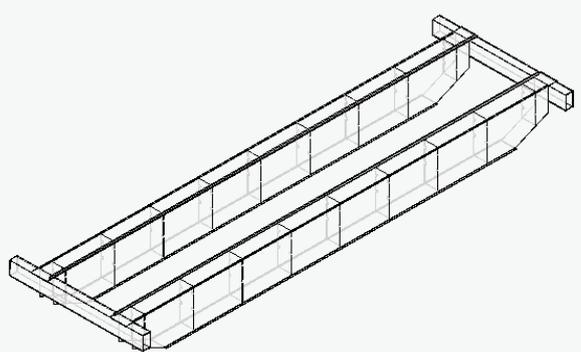Fig. 3: Elements used to model an overhead crane girder

4 Solid and finite element modelling of an overhead crane bridge

The finite element method is a numerical procedure that can be applied to obtain solutions to a variety of problems in engineering. Steady, transient, linear or nonlinear problems in stress analysis, heat transfer, fluid flow and electromechanism problems may be analysed with finite element methods. The basic steps in the finite element method are defined as follows: preprocessing phase, solution phase, and postprocessing phase.

Real crane data was gathered from CESAN Inc., a Turkish company involved in mass production of overhead cranes. First, the crane bridge is modeled as a surface. Bridge geometry is suitable for this, and long and thin parts should also be modeled as a surface. Later, a mesh is created. In this study, a quadratic element type is used. Solid modeling is generated for the calculated crane bridge and the solid model is shown in Fig. 4 [20].

5 Numerical example of an overhead crane

A 35-ton-capacity overhead crane of overall length 13 m and total weight 22.5 tons was selected as a study object. The configuration of the overhead crane is shown in Fig. 1. The overhead crane consists of two girders, two saddles to connect them, and a trolley moving in the longitudinal direction of the overhead crane and wheels. The driving unit is installed in one of the two girders. The overhead crane is supported by two rails and the runway girders installed in building.

In order to calculate the stress in the structure, the rules of F. E. M 1.001 are applied. The design values used in the bridge analysis from the F. E. M and DIN standards are given in Table 1.

Table 1: Bridge property values

Handling Capacity	: $G_y = 35$ ton
Trolley Weight	: $F_A = 3$ ton
Bridge Length	: $L_K = 13$ m
Distance between wheels of trolley	: $L_A = 2$ m
Trolley Velocity	: $V_A = 20$ m/min.
Crane Velocity	: $V_F = 15$ m/min.
Hoisting Velocity	: $V_H = 2.7$ m/min
Total duration of use	: U4
Load spectrum class	: Q3
Appliance group	: A5
Loading type	: H (main load)
Dynamic coefficient	: $\psi = 1.15$
Amplifying coefficient	: $\gamma_c = 1.11$

First the maximum and minimum stresses and then the shear stress are calculated using the F. E. M. rules. Using the finite element method for the considered girder, we obtain the stress valnes. We obtain the static loads due to the dead weight, the loads due to the working load multiplied by the

Solid model of a crane bridge

Wireframe view of a crane bridge

Fig. 4: Models of an overhead crane bridge

dynamic coefficient, and the two most unfavourable horizontal effects, excluding the buffer forces.

The maximum stress consists of the stress on the bridge dead weights, the stress on the trolley dead weight, the stress from the hoisting load, stress from the inertia forces and the stress of the trolley contraction. The minimum stress includes the stress on the bridge dead weights and the stress on the trolley dead weight. The maximum and minimum stresses for the given values according to the F. E. M. rules [20] are written in standard form as

$$\sigma_{\max} = \gamma_c \left\{ \frac{(q_K + q_P)\, g \cdot L_K^2}{8 W_{X1}} + \frac{F_{AA}}{32 L_K \cdot W_{X1}} (2L_K - L_A)^2 \right.$$

$$+ \psi \frac{F_Y}{32 W_{X1} \cdot L_K} (2L_K - L_A)^2$$

$$+ \frac{0.075 L_K}{W_{Y1}} \left[(q_K + q_P)\, g \cdot L_K + \frac{F_{AA}}{2} \right] \qquad (1)$$

$$\left. + \frac{0.05 L_A}{W_{Y1}} (F_{AA} + F_Y) \right\}$$

and,

$$\sigma_{\min} = \gamma_c \left[\frac{(q_K + q_P)\, g \cdot L_K^2}{8 W_{X1}} + \frac{F_{AA}}{32 L_K \cdot W_{X1}} (2L_K - L_A)^2 \right]. \quad (2)$$

The value of the dynamic coefficient ψ is applied to the loading arising from the working load. The value of the amplifying coefficient γ_c depends the group classification of the application, and the weight of one meter maintenance platform is zero in this work. [25].

It is assumed that the total load (372780 N) is effected on the mid point of the rail and each girder shares this total load equally. This load is applied via the contact points of the two trolley wheels in this system. Therefore the value of the acting force on each point is 93195 N. Applying the total load in the system, the value of the maximum stress according to Eq. (1) is 143.90 N/mm^2 to two decimal places, and the value of the minimum stress according to Eq. (2) is 47.33 N/mm^2 to two decimal places.

According to Fig. 5, the permissible stress in shear consists of the shear stresses of the wheel forces, and is defined as [20]

$$\tau = \frac{(x_4 + 0.2 y_5) \cdot (F_{AA} + F_Y)}{4 t_2 (x_2 + x_4) \cdot (y_1 + y_3)} + \frac{\psi \cdot F_Y + \gamma_c \cdot F_{AA}}{4 t_2 \cdot h_2}. \qquad (3)$$

The value of the maximum shear stress is 24.82 N/mm^2 to two decimal places from Eq. (5). Substituting Eq. (1)–(3) the equivalent stress is given by. The value of the equivalent stress is 150.18 N/mm^2 to two decimal places.
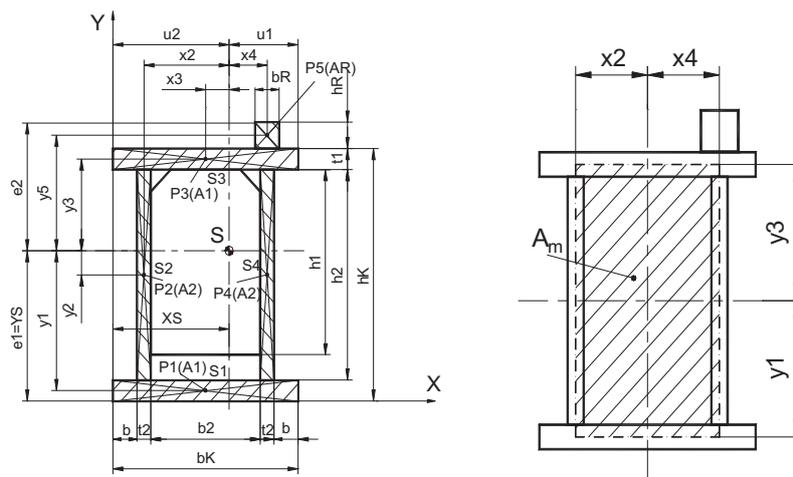

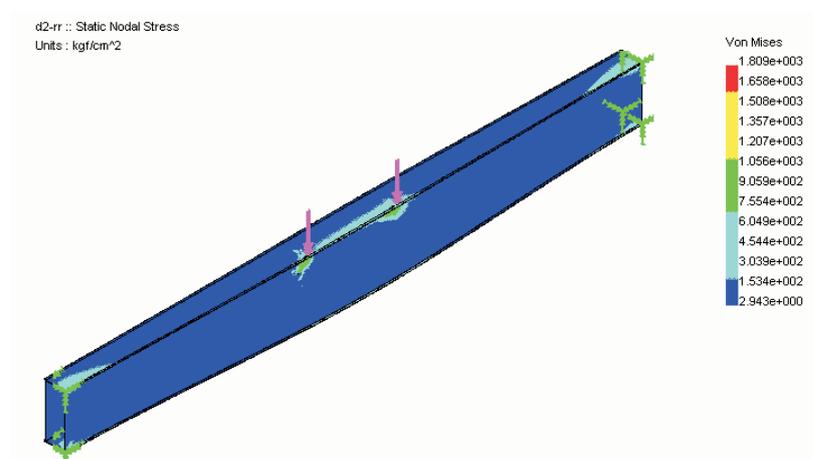Fig. 5: Inertia and moment of resistance in a box girder

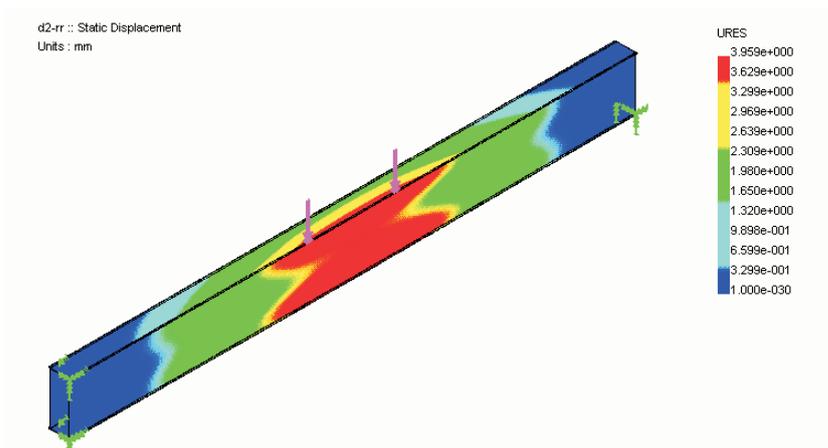Fig. 6: Stress values of an overhead crane girder with a four-node tetrahedral element

http://ctn.cvut.cz/ap/

Fig. 7: Displacements of an overhead crane girder with a four-node tetrahedral element

6 Results from a girder model with a four-node tetrahedral element

To model the overhead crane girder with a four-node tethrahedral element, Cosmosworks software was used for finite element analysis using the girder solid model generated by means of SolidWorks 2003. Young's Modulus (E) is 2.1×105 N/mm^2 and the Poisson Ratio (ν_{St}) is 0.3 for finite element analysis. The value of the maximum stress of the side plate is 12.07 N/mm^2 to two decimal places and the value of the maximum stress of the bottom plate is 15.08 N/mm^2 to two decimal places from Fig. 6 [20].

The displacement of the modelled overhead crane girder was obtanied from CosmosWorks, and is illustrated in Fig. 7. The value of maximum displacement of the girder is about 2.2 mm.

7 Results from a girder model with a four-node quadratic shell element

To model the overhead crane girder with a four-node quadratic shell element, MSC Patran software was used for the finite element analysis. Young's Modulus (E) is 2.1×10 N/mm^2 and the Poisson Ratio (ν_{St}) is 0.3 for finite element analysis. The value of the maximum stress of the side plate is 35.40 N/mm^2 to two decimal places, and the value of

the maximum stress of the bottom plate is 49.30 N/mm^2 to two decimal places, from Fig. 8 [20].

The displacement of the modelled overhead crane girder was obtained from MSC Patran, and is illustrated in Fig. 9. The value of maximum displacement of the girder is about 3.89 mm.

The value of the maximum stress according to Eq. (1) is calculated as 143.90 N/mm^2 to two decimal places. The safety factor should be considered between 2 and 3 for overhead crane girder design. The maximum stress value of the side plate is between 24.14 and 36.21 N/mm^2 to two decimal places, and the maximum stress value of the bottom plate is between 30.16 and 45.24 N/mm^2 to two decimal places for a four-node tetrahedral element, taking into account the safety factor.

The maximum stress value of the side plate is between 70.8 and 106.2 N/mm^2 to two decimal places and the maximum stress value of the bottom plate is between 98.6 and 147.9 N/mm^2 to two decimal places for a four-node quadratic shell element, taking into account the safety factor.

The permissible displacement of the girder is 13 mm according to F. E. M. rules. The maximum displacement obtained from the finite element model with a four-node tetrahedral element is between 4.40 and 6.60 mm, taking into account the safety factor. The maximum displacement obtained from the finite element model with a four-node quadratic shell element is between 7.78 and 11.67 mm, taking into account the safety factor.
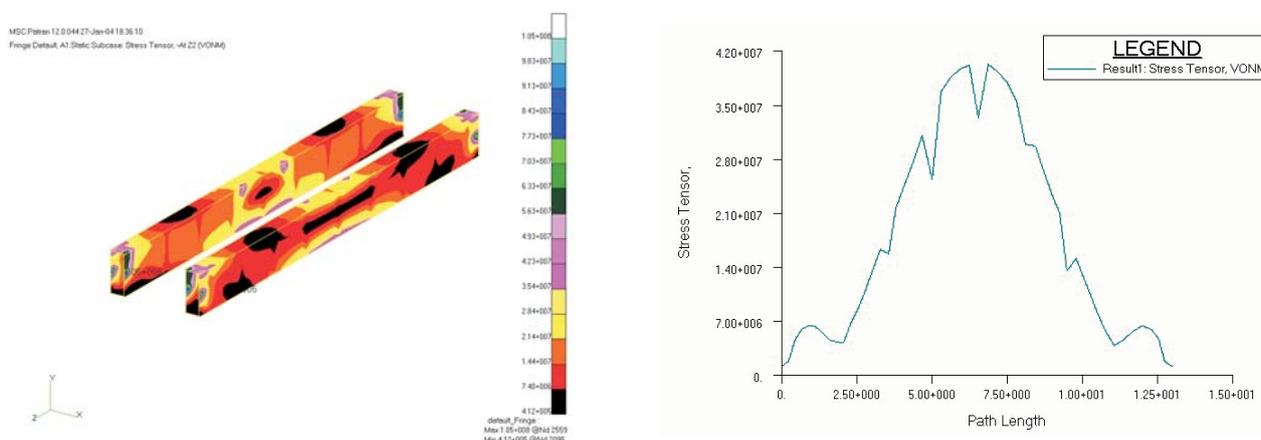

Fig. 8: Stress values of an overhead crane girder with a quadratic shell element
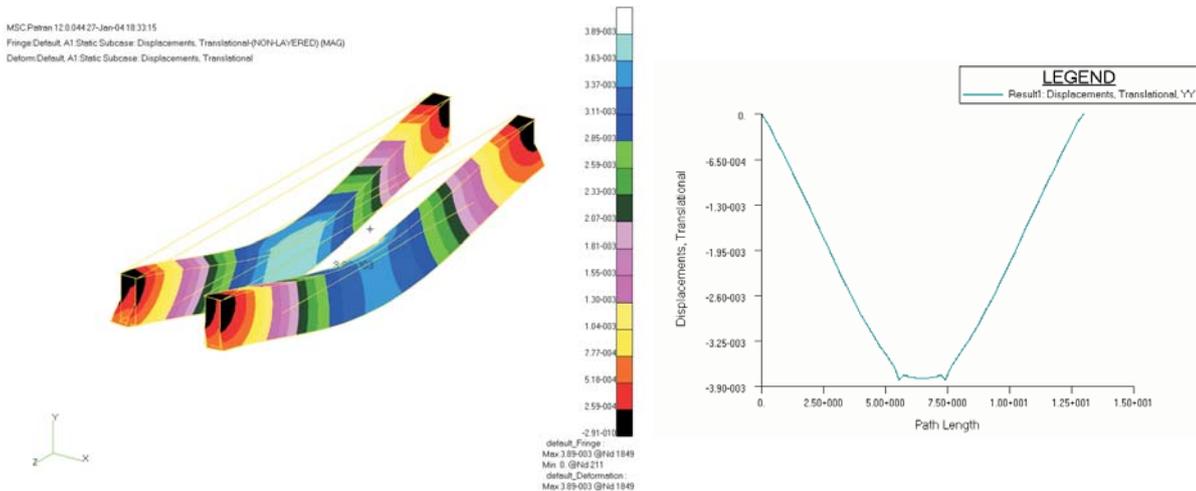
Fig. 9: Displacements of an overhead crane girder with a four-node quadratic shell element

8 Conclusion

In this study, unlike the other studies carried out previously, shell elements in finite element modeling of an overhead box girder have been examined. In order to show the use of shell elements, one illustrative overhead crane bridge example is given. The maximum stress value is 143.90 N/mm^2 and 45.24/mm^2 for a four-node tetrahedral element and 147.9 N/mm^2 for a four-node quadratic shell element using both calculations according to the F. E. M. Rules and finite element analysis. The value of the equivalent stress is 150.18 N/mm^2 to two decimal places. Taking into account the safety factor, the stress value varies between 97–145.5 N/mm^2, which is obtained from MSC Patran.

The ratio of length to thickness of the element used in modelling the overhead crane box girder is higher than 20. Therefore, in order to show the accuracy of the analysis of the overhead crane bridges, a four-node quadratic shell element is used instead of the four-node tetrahedral element for finite element analysis.

Acknowledgment

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Coskun Alkin

Dr. C. Erdem Imrak
e-mail: imrak@itu.edu.tr

Dr. Hikmet Kocabas

Istanbul Technical University
Faculty of Mechanical Engineering
34439 Istanbul, Turkey