STRESSES AND STRAINS IN A TORPEDO POT FOR CAST IRON

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Abstract: The adopted design of a new prototype of a torpedo pot used for the transportation of the liquid cast iron is verified by analyzing experimentally and numerically its model made at a scale 1:8. The comparison between the results obtained with strain gage measurements and FEM led to a thorough knowledge of the strain and stress distributions. Knowing the most dangerous stress concentration areas a new design optimization process could be accelerated without becoming unreliable.

Keywords: stress, strain, strain gauge, FEM, torpedo pot, cast iron

1. INTRODUCTION

Cast iron is characterized by relatively low melting point, good fluidity and resistance to deformation and wear and due to its excellent machinability have become an engineering material with a wide range of applications such as: pipes, machines and automotive industry parts [1].

In production facilities cast iron is heated until it liquefies and is then poured into a mould to solidify. The transportation of the liquid cast iron within the ironworks is done with a wagon consisting of a torpedo pot, two bogies which support the pot and have four axles each and the modular steel beams. At one end of the wagon is placed the driving mechanism of the torpedo pot and the control equipment (Fig. 1).

The torpedo pot is a self-supporting structure consisting of a central cylindrical shell with two tapered coating ends. In the upper central part of the cylindrical shell is cut a window for loading and emptying of liquid cast iron [2]. The capacity of the interior of the torpedo pot is about 300 t of liquid cast iron when the masonry is new and about 365 t when the masonry is used.

In order to verify the adopted solution for a prototype of a new torpedo pot design, an experimental investigation and a numerical analysis consisting in the determination of the strain and stress distributions in the model of the torpedo pot using the strain gauge measurements and the FEM was performed. The experimental analysis consisted of strain gauges measurements because a thorough knowledge of the stress state in the structure called for accurate determination of the strains present.

The results obtained using the comparative study, experimental and numerical, led to a more accurate identification and evaluation of the most dangerous stress concentration zones of the structure and should find important use in torpedo pot design optimization.

2. EXPERIMENTAL INVESTIGATION

The model of the prototype used for the experiment was made at the scale 1:8 and had no chamotte in the interior. The model was loaded with metal shot whose total weight was about 700 kg. The mass of metal shot modeled the liquid cast iron and the chamotte.

The experimental investigation consisted of the measurements of the normal strains [3, 4, 5] by applying strain gauges in various points of the outer surface of the model. These points belonged to the vertical median plane of symmetry, to the transverse plane of symmetry and to the regions with concentrators (window area and the areas of transition from cylindrical to conical shell).

On the median and transverse planes were applied 17 rosette strain gauges each having two transducers perpendicular to each other: one of the transducers was oriented along the longitudinal direction (the having

Fig. 1. Design of the torpedo pot wagon

therefore the direction of the tangent at the point. These directions represent the directions of the principal stresses for the symmetrical loading with respect to the longitudinal plane.

In the stress concentration areas which are not located in the planes of symmetry were applied rosettes with three strain gauges along the directions that are at 45° between them (points 4, 6, 9 and 10).

On one of spindles of the models were applied simple transducers (points 22 and 23).

All strain gages were manufactured by Hottinger-Baldwin. Two strain gauge bridges and six switch boxes produced by Vishay have been used. The strains were measured for the case of loading corresponding to filling and emptying of the model with metal shot. These gave a vertical load of $G_m \approx 7$ kN, the model being with the longitudinal plane of symmetry in vertical position.

The location of the strain gauges applied on the structure is presented in Fig. 2 and Fig. 3.

Fig. 2. Photograph of the experiment

Fig. 3. Location of the strain gauges

Strains denoted by ε_L and ε_T were measured at points where strain gauge transducers on two directions L (longitudinal) and T (transversal) have been applied. They represent the principal strains in the points situated in the planes of symmetry. At points where strains gages on three directions at 45° were applied, the principal strains ε_1 and ε_2 have been determined with the relationship [6]:

$$\varepsilon_{1,2} = \frac{1}{2}(\varepsilon_a + \varepsilon_c) \pm \frac{1}{\sqrt{2}} \sqrt{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2} \quad (1)$$

ε_a , ε_b and ε_c are the strains measured along the three directions a , b , c of the strain gauge.

The principal stresses σ_1 and σ_2 were calculated using the following equations [7]:

- for strain gauge on one direction:

$$\sigma_1 = K \cdot E \cdot \varepsilon \quad (2)$$

- for strain gauges on two directions:

$$\sigma_1 = K \frac{E}{1 - \vartheta^2} (\varepsilon_L + \vartheta \varepsilon_T) \quad (3)$$

$$\sigma_2 = K \frac{E}{1 - \vartheta^2} (\varepsilon_T + \vartheta \varepsilon_L)$$

where K is a correction factor depending on the constants of the transducer, $E = 2.1 \times 10^5$ MPa is the modulus of elasticity of steel and $\vartheta = 0.3$ is Poisson's ratio;

-for strain gauges on three directions:

$$\sigma_1 = K \frac{E}{1 - \vartheta^2} (\varepsilon_1 + \vartheta \varepsilon_2) \quad (4)$$

$$\sigma_2 = K \frac{E}{1 - \vartheta^2} (\varepsilon_2 + \vartheta \varepsilon_1)$$

The values of the measured strains ε , ε_L and ε_T , ε_a , ε_b and ε_c together with the calculated principal stresses σ_1 and σ_2 in some of the points where strain gauges were placed on the model of the torpedo pot loaded with metal shot with $G_m \approx 7$ kN are listed in Table 1.

The transition from model to prototype was made considering the lengths scale k_l and k_F the forces scale. Considering that the torpedo pot is subjected especially to bending, from Navier's equation [8] results that the stress is directly proportional to the bending moment (i.e. to the product $k_l \cdot k_F$) and inversely proportional to the section moduli scale k_l^3 . Thus the stresses in the prototype σ_p can be determined using the formula:

$$\sigma_p = \frac{k_F \cdot k_l}{k_l^3} \cdot \sigma_m$$

with σ_m being the stresses in the model. The latter are calculated for the load G_m that corresponds to the prototype load $G_p = k_l^3 \cdot G_m = 8^3 \cdot 7 = 3584$ kN. According to the design specifications, the maximum load for the pot is approximately 3650 kN. Adding also the own weight of the torpedo pot (the used masonry inclusively) the total load will be about 5000 kN. Hence

$$k_F = \frac{5000}{7} = 714$$

$$k_\sigma = \frac{714}{8^2} = 11.15$$

Measurement point	Transducer	$\varepsilon \times 10^{-6}$	σ_1	σ_2
2	2.1	-31.7	-41.6	-82.3
	2.2	-7.7		
4	4.1	-27.3	-61	-76
	4.2	-18.6		
	4.3	-25.3		
6	6.1	-16.7	36.7	-26.9
	6.2	20		
	6.3	9.7		
7	7.1	-9.7	38.2	-9.9
	7.2	18.7		
9	9.1	-15.7	46.4	-22.8
	9.2	23.7		
	9.3	13.3		
10	10.1	-27.6	-61	-77.7
	10.2	-19.3		
	10.3	-26.7		
12	12.1	-26.7	-25.9	-66.6
	12.2	-2.7		
17	17.1	19.7	52	28.9
	17.2	6		
22	22	5	10.3	-

Tab. 1 Measured strains and calculated principal stresses

Finally, in order to obtain the values of the stresses in the prototype of the torpedo pot, the stresses in the model must be multiplied by $k_\sigma = 11.15$.

3. FINITE ELEMENT ANALYSIS

A finite element analysis was performed using SOLIDWORKS software[9]. The finite element mesh for the model of the torpedo pot (Fig. 4) was generated using 3D tetrahedral elements []. Both the applied load and the boundary conditions used for the finite element model (Fig. 5) were chosen to be similar to those of the model experimentally investigated.

Fig.4 Finite element mesh

Fig. 5. Applied load and boundary conditions

The contour plots of the displacements, of the principal strains ε_1 and ε_2 are plotted in Fig. 6, Fig. 7 and Fig. 8 respectively. In Fig. 9, Fig. 10 and Fig. 11 the contour plots of the principal stresses σ_1 and σ_2 , and those of von Mises stresses respectively are presented.

Fig. 6. Displacements

Fig.7 Principal strains ε_1

4. CONCLUSIONS

The strain and stress analysis of the model of a torpedo pot used for the transportation of the liquid cast iron performed experimentally and numerically led to the conclusions:

Fig.8 Principal strains ε_2

Fig.9 Principal stresses σ_1

Fig.10 Principal stresses σ_2

Fig.11 Contour plots of von Mises stresses

a. In both analyses with the strain gauge measurements and FEM it was noticed that in the points located at the top of the pot and also in the area of the window used for filling and emptying, the strains and stresses have higher values than in other points. The maximum measured stress -82.3 MPa occurs in the measurement point 2 (Table 1).

b. Comparing the values of the principal strains ε_1 and ε_2 determined by means of the measured strains listed in Table 1 with the values obtained using FEM (presented in Fig. 7 and Fig. 8) and correspondingly the values of the principal stresses σ_1 and σ_2 (Table 1) with those from Fig. 9 and Fig. 10, it can be remarked that in general the agreement between the measured and the calculated results is good. However, differences were found, sometimes noticeable. These can be explained due to the manufacturing technology of the model, which was made of rolled and welded steel plates. The welds were asymmetrical with respect to the geometric planes of symmetry and this could not be modeled with FEM.

c. In some other points situated symmetrically about the transverse plane of symmetry (Fig. 3) were observed noticeable differences between the values of the principal stresses (Table 1). This can be explained by the presence of the residual stresses in the vicinity of the weld seams that assembled the steel rolled plates.

d. The numerical study reveals that high values of the displacements occur at the bottom of the model of the torpedo pot (Fig. 6), and high values of the von Mises stresses can be found in the area of the window.

e. This comparative analysis provides useful information about the general stress state of the investigated structure, identifying the most dangerous stress concentration zones. The information given by this study can be used for a future optimization of the structural shape of the prototype of the torpedo pot, in order to finally obtain reduction of the consumption of materials.

5. REFERENCES

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