Fatigue cracks in castellated I-beams under cyclic loads

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Abstract. The numerical calculation is carried out to predict the places of fatigue cracks, determine the fatigue life and the path of crack propagation of castellated beams, specifying the possibility of their use under multi-cycle loads. The method was implemented by using of the developed subroutine in the Ansys Mechanical software package in the parametric programming language APDL (ANSYS Parametric Design Language). The calculation is carried out in the form of successive quasi-static iterations.

1. Introduction
Castellated beams are often used as supporting structures that work on bending. It turns out that they work quite well under static loads and there is the possibility of saving material and lightening the weight of building structures. The aim of the work is to study the applicability of castellated beams under cyclic modes of operation, taking into account the accumulation of damage, the formation of fatigue cracks and the trajectory of their propagation. The object of researching in this article is fatigue damage arising from the cyclic loading process at stresses exceeding the material fatigue limit.

In the previous article by the authors [1], a methodology was developed for assessing fatigue damage and crack propagation. This algorithm makes it possible to evaluate the stresses acting near the holes, determine the number of loading cycles at which a defect occurs and establish the direction of its development. The study of the applicability of castellated I-beams was developed based on the finite element method using the ANSYS Mechanical APDL program.

2. Research
We estimated the durability at the stage of cracking on the basis of the actual characteristics of the mechanical properties of the metal by based on the methods of N. A. Makhutov [2-4], which proved itself in the analysis of critical components and elements:

\[ \sigma_a^* = \frac{E}{4(N)^m_p} \left( \frac{100}{100 - \psi_k} + \frac{S_k}{4(N)^m_e} \right) \ln \left( \frac{1 + r}{1 - r} \right) \]  

In this equation: \( \sigma_a^* \) – amplitude of conditional elastic stresses in the most loaded zones, equal to \( \sigma_a = e_a E \) (\( e_a \) is the amplitude of the elastic or elastic-plastic local deformation, \( E \) is the elastic modulus); \( \psi_k \) – relative narrowing of the sample (in %); \( S_k \) – tear resistance in the neck; \( m_e \) – characteristic (indicator) of low-cycle fatigue resistance; \( m_e \) – characteristic (indicator) of resistance to...
high-cycle fatigue; $r$ – asymmetry coefficient of the cycle of local stresses in the zone under consideration; $r^*$ – asymmetry coefficient of the strain cycle.

The solution of the fatigue resource and crack propagation problem was implemented by using a subroutine in the parametric programming language APDL (ANSYS Parametric Design Language). In the equation (1), reverse substitution was implemented. Using the well-known $\sigma^a$, the parameter $N$ is determined iteratively with a step $n$.

Subsequently, the elastic modulus is decreases (on 2 order) for the most stressed element and the variable $N$ is stored, which shows the number of loading cycles. Next, a comparison is made with the maximum permissible crack length and the calculation continues in the cycle until the crack length reaches this value.

Plotting the function of the size of the crack to the number of cycles allows us to determine the zone of stable and accelerated crack growth. An analysis of these graphs makes it possible to identify threshold values of loading cycles at which a sharp increase in the growth rate of fatigue cracks occurs and take measures to reduce the negative impact of fatigue phenomena in the operation of structures.

The main advantage of this method is the use of the computational cyclic algorithm in the programming language APDL (ANSYS Parametric Design Language), which implements the entire process of the solution in both linear and nonlinear formulations.

The block diagram of this algorithm (in a linear formulation) is presented below in figure 1.

Based on the above methodology, the resource of a castellated I-beam was analyzed (figure 2). As loading, a transverse asymmetric load $P$ with an asymmetry coefficient of $R = 0.1$ was chosen. The value of the load $P$ was chosen from the condition that the fatigue stress limit was exceeded, but less than the yield strength of the material.

The calculations are carried out in a formulation that allows linear and nonlinear three-dimensional modeling to evaluate fatigue phenomena, and resource estimates, in which the applied calculation model reflects the work of the I-beam. Formulation of the problem is to consider the fatigue strength of castellated beams under the action of cyclic loads, to determine the number of loading cycles at which a defect occurs, and to determine the direction of its propagation.

The characteristics of steel with a yield strength of 245 MPa were used as initial data for modeling the material. Finite elements such as Shell 181 were used. They are suitable for the analysis of thin and moderately thick shells. This is a four-node element with six degrees of freedom in each node: displacements in the $x$, $y$, and $z$ directions and rotations around the $x$, $y$, and $z$ axes. Shell 181 is well suited for non-linear applications with linear, large rotation and large deformation. The change in shell thickness is taken into account in nonlinear analyzes. The wording of the element is based on the logarithmic deformation and measurements of the true stress. The kinematics of the element takes into account the final deformation of the membrane (tension). However, changes in curvature with time increment are assumed to be small [5].

The studies were carried out for an asymmetrically loaded beam (with a shift from the center of the span towards the left support) in order to get rid of the effect of symmetry and cracking at different ends of the beam.

The most common beam support was considered – articulated, which in a three-dimensional finite element setting was implemented as follows: the movement of nodes located on the lower and upper lines of the extreme sections of the beam in the directions perpendicular to the axis of the beam was taken to be zero. It was also prohibited the horizontal movement of the node on the left edge of the beam at the level of the neutral axis.

The formulation of the problem of the resource of the beam and the propagation of cracks according to the considered methodology [1] implies a division into 2 stages of solution:

1. Preliminary stage. Characterized by a less accurate finite element mesh for quick calculation. This stage is characterized by determining the places of development of cracks and determining the main direction of crack growth. This stage shows the qualitative distribution of cracks in the construction.
2. The final stage. It is characterized by a more accurate finite element mesh and refinement in zones in which cracks occurred at the preliminary stage. This stage is characterized by a more accurate determination of the propagation of the development of cracks and the determination of the number of cycles at which the design resource is exhausted during cyclic loading. This stage shows the quantitative distribution of cracks in the construction.

![Block diagram of the linear algorithm](image)

**Figure 1.** A block diagram of the linear algorithm [1]

The parameters of the model under consideration are presented in figures 2 and 3. The beam length is 6 m, number of holes – 10. The finite elements mesh of the preliminary stage was chosen 20x20 mm. The results of the calculation are the directions of the propagation of cracks and a graph of the dependence of the propagation of cracks on the number of cycles. In figures 4, 5, and 6 present some results of calculating a castellated beam.
Figure 2. Fragment of FEM model of castellated I-beams

Figure 3. Geometric parameters of the I-beam

Figure 4 places of occurrence of cracks are shown and the main directions of its propagation are determined. In figure 5 isofield of the main tensile stresses $\sigma_1$ (MPa) are presented, by which the unknowns in the Makhutov equation are determined. Figure 6 shows a graph of the dependence of the crack length on the number of loading cycles.

As the result has shown from the calculation, fatigue cracks arise near the corners of the holes, called stress concentrators. The propagation of a fatigue crack occurs at an angle of $45^0$ and tends to reach the upper flange of an I-beam castellated beam. The exhaustion of the bearing capacity is due to the inability of the remaining cross section of the beam to resist the existing stresses.

Figure 4. Fatigue calculation results and crack propagation directions in castellated I-beam
Consider the final stage of the calculation. Based on the above calculations at the preliminary stage, we determine the most dangerous zones where fatigue cracks occur. The refinement of the finite element mesh in the zones of crack formation makes it possible to analyze the nature of the motion of the crack and determine the quantitative characteristic of the cracks.

At the final stage of the calculation, the finite element mesh was 15x15 mm with refinement (NREFINE command) in the zones of cracking in the previous stage of calculation (figure 7).

**Figure 5.** Main tensile stresses $\sigma_1$ (MPa)

**Figure 6.** Graph of crack propagation versus number of cycles

**Figure 7.** FEM model of a castellated I-beam with refinement around tired elements
Based on the above calculations, we have the following picture of crack formation. The largest crack occurred in the upper right corner of the 1st holes from the zone, the distribution of which is shown in figure 8.

![Crack Formation Diagram](image)

**Figure 8.** The results of the updated fatigue calculation and the direction of propagation of crack No. 1

A graph of the dependence of crack No.1 propagation on the number of cycles of a given crack is shown in figure 9.

![Graph of Crack Propagation](image)

**Figure 9.** Graph of the propagation of cracks No.1 to the number of cycles.

As shown from the graph of dependence, the resource of this castellated beam is about 70 thousand cycles (figure 9).

In addition to the growth of the largest crack (crack No.1), at the same time two more cracks grew (crack No.2 and crack No.3), which have a shorter length, but arose due to the peak values of the stress state in these areas during the iteration calculation (figure 10).

The main tensile stresses of the final stage of the calculation are presented in figure 11.

Further development of the method involves solving the following tasks:
1. Expanding the range of tasks.
2. Creation of a universal resource estimation algorithm for arbitrary metal construction.
3. Consideration when optimizing the metal consumption of construction.
3. Conclusions

1. The resource of a castellated I-beam under a cyclic load was analyzed using a previously developed technique, the result of which was a qualitative and quantitative assessment of its performance.

2. It has been established that its resource for the tested nature of loading is only $7 \times 10^4$ cycles, which may not be enough.

3. Based on the numerical calculations, it can be concluded that it is advisable to use castellated beams only under static loads, and their suitability for work is possible only in cases where there is no multi-cyclic mode of operation of the structure throughout its life.

4. This technique in the future will allow predicting the occurrence of cracks, which will improve the quality of visual inspection of structures operating under cyclic loading.

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