Development of Force Limiters in Mobile Rod Structures of Demountable Type

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Abstract. Large-scale mass events (sports, entertainment, etc.) require safe and high-quality organization of the visual and stage sector, so there is a need for pre-fabricated and mobile rod structures. To solve such problems, it is convenient to use the Layher system of modular building structures. The criterion for design failure is the failure of one of the most loaded elements, even when the entire system as a whole still has some resource. Compensating devices can be a solution to this problem. This study solves the problem of redistribution of forces in the rods using compensating devices, taking into account the stress state of the rod system. In the event of failure of one or more elements, their internal forces are redistributed between adjacent elements in proportion to their stiffness, so spatial rod systems can fairly well resist progressive destruction. However, the destroyed element does not carry any further load and adjacent elements can also fail. Compensating devices leave overstressed rods in operation and thus increase the load-bearing capacity of the rod system. The invention relates to the field of construction and mechanical engineering, namely to rod metal structures and their elements that work on tension or compression, primarily in statically indeterminate systems. The purpose of the invention is to obtain stable axial forces in a limited range separately for compression and stretching with the possibility of adjusting their size and length of the element. This goal is achieved by the fact that in the process of manufacturing the force limiter, which includes coaxial rod elements with a collet clip, the contact surfaces are made with ring waves (teeth), which can have a sinusoidal, triangular and trapezoidal profile with different angles of inclination of the sides. The height and pitch of the ring waves are assigned from the conditions for performing the calculated range and speed of loads, and the angle of inclination of the profiles from the conditions for ensuring different rates of change in forces (compression/stretching). Arbitrary schemes have been studied, the use of compensating devices in which allows reducing the metal content of the structure by 20%. A compensating device was developed and calculated. An experiment was conducted to identify the redistribution of forces between elements when using compensating devices: the results generally coincide with theoretical calculations.

1. Introduction
The purpose of this work is to obtain stable axial forces in a limited range separately for compression and stretching with the ability to adjust their size and length of the element.
For structures with a mass presence of people, there are increased requirements for ensuring the levels of both safety and security. There is a need to study the actual operation of the structure as a whole, as well as individual core elements.

The system of modular rod structures is statically indeterminate, so there is a problem of uneven distribution of forces in the rods. The solution to this problem can be compensators (force limiters), which redistribute efforts in the system so that overloaded elements are unloaded, and underloaded ones are included in the work.

The criterion for design failure is the failure of one of the most loaded elements, even when the entire system as a whole still has some resource. Compensating devices can be a solution to this problem. This study solves the problem of redistribution of forces in the rods using compensating devices, taking into account the stress state of the rod system.

In the event of failure of one or more elements, their internal forces are redistributed between adjacent elements in proportion to their stiffness, so spatial rod systems can fairly well resist progressive destruction. However, the destroyed element does not carry any further load and adjacent elements can also fail. Compensating devices leave overstressed rods in operation and thus increase the load-bearing capacity of the rod system.

2. Numerical study

Figure 1 shows a force limiter with coaxial rod elements 2, 4 and threaded rings 3. It is a collet clip, the contact surfaces of which in the longitudinal section have the form of a trapezoid.

![Figure 1. Collet type compensator](image)

Figure 2 shows the profiles of the contact surface with asymmetric triangular and trapezoidal (with gaps) shapes.

![Figure 2. Execution of the contact surface](image)

Figure 3 shows options for making the contact surface at an angle to the axis of the connected elements.

![Figure 3. Contact surface at an alpha angle](image)

Figure 4 shows a variant of the limiter, with several teeth on the clamp lobes, for more reliable contact of elements 2 and 4.

1. The force limiter works as follows. When the upper calculated range limit, equipped with threaded rings 3, is reached in the limiter, the collet clamp lobes open and the element 4 is shifted relative to the element 2 by one ring wave (tooth) with the unloading of the system in which the limiter is installed to the lower limit of the force. Pre-calibration of the limiter force range is performed using threaded rings 3.
2. The force limiter of the system element, which includes coaxial elements with a collet clip and a ring, differs in that the contact surfaces of the clip are made with ring waves (teeth), which can have sinusoidal, triangular, trapezoidal profiles with different angles of inclination of the sides;

3. The force limiter of the system according to claim 1 differs in that the contact surface can be made at an angle to the axis of the limiter;

4. The force limiter of the system according to claim 1 differs in that the waves of the contact surface can be made in the form of a thread;

5. The force limiter of the system according to claim 1 differs in that the limits of the range of operation of the limiter are calibrated by threaded rings 3 (the second ring serves as an improvised locknut).

![Figure 4. Compensator with multiple “teeth”](image)

The main elements of the collet mechanism are steel blades in the form of rectangular plates. To determine the geometric parameters of the plates, we use the O. Mohr method as well as the Simpson method (formula)

\[
\Delta = M_p \times MT = \frac{l}{6} (3000 \cdot l^2 + 4 \cdot 1500 \cdot l \cdot \frac{1}{2}) \frac{1}{EI} = 0.005; \tag{1}
\]

\[
\frac{0.1}{6} (3000 \cdot 0.1 \cdot l^2 + 4 \cdot 1500 \cdot 0.1 \cdot \frac{1}{2}) \frac{1}{EI} = 0.005 \tag{2}
\]

\[
\frac{1}{EI} = 0.005 \Rightarrow I = \frac{200}{20.6 \cdot 10^{10}} = 9.71 \cdot 10^{-10} \tag{3}
\]

\[
I = \frac{bh^3}{12} = 9.71 \cdot 10^{-10} \Rightarrow \frac{h^3}{12} = 9.71 \cdot 10^{-10} \Rightarrow h = \frac{\sqrt[3]{1.1652}}{1} \approx 1cm \tag{4}
\]

\[
\Delta = M_p \times MT = \frac{l}{6} (125 \cdot l^2 + 4 \cdot 62.5 \cdot l \cdot \frac{1}{2}) \frac{1}{200} = 0.005; \tag{5}
\]

\[
\frac{41.67 \cdot l^3}{200} = 0.005 \Rightarrow l = \sqrt[3]{\frac{1}{41.67}} = 0.29 \approx 30cm \tag{6}
\]

After determining the initial geometric parameters using the O. Mohr method as well as the Simpson method (formula), we calculate the maximum load per steel blade. To determine the load, we use the balance of forces. When calculating, we estimate the angle of inclination as 45 degrees.

\[
\sum Y = 0: \tag{7}
\]

\[
-F \cdot \cos \alpha - N_x + F_x = 0 \tag{8}
\]

\[
\sum Y = 0: \tag{9}
\]

\[
-F \cdot \sin \alpha - N_y + F_y = 0
\]
To simplify the expressions, we add them up by multiplying the equation of the Y-axis by the sliding coefficient with a minus sign \((-\mu)\), and in the equation relative to the X-axis we replace the friction force with the corresponding resultant expression \((F_r = F_{\perp} \cdot \mu)\).

We get a system of equations:

\[
\begin{align*}
\mu \cdot F \cdot \cos \alpha + \mu \cdot N_{\perp} - \mu \cdot F_{\perp} &= 0 \\
F \cdot \sin \alpha - N_{\parallel} + \mu \cdot F_{\perp} &= 0 \\
\Rightarrow & \quad \begin{cases} 
F(\mu \cdot \cos \alpha + \sin \alpha) + \mu \cdot N_{\perp} - N_{\parallel} = 0 
\end{cases}
\end{align*}
\]

(11)

\[
\begin{align*}
\Rightarrow & \quad \begin{cases} 
F = \frac{N_{\parallel} - \mu \cdot N_{\perp}}{\mu \cdot \cos \alpha + \sin \alpha} 
N_{\parallel} = N \cdot \cos \alpha 
N_{\perp} = N \cdot \sin \alpha 
\end{cases}
\end{align*}
\]

(12)

\[
\begin{align*}
\mu \cdot F \cdot \cos \alpha + \mu \cdot N_{\perp} - \mu \cdot F_{\perp} &= 0 \\
F \cdot \sin \alpha - N_{\parallel} + \mu \cdot F_{\perp} &= 0 \\
\Rightarrow & \quad \begin{cases} 
F(\mu \cdot \cos \alpha + \sin \alpha) + \mu \cdot N_{\perp} - N_{\parallel} = 0 
\end{cases}
\end{align*}
\]

(13)

\[
\begin{align*}
\Rightarrow & \quad \begin{cases} 
F = \frac{N_{\parallel} - \mu \cdot N_{\perp}}{\mu \cdot \cos \alpha + \sin \alpha} 
N_{\parallel} = N \cdot \cos \alpha 
N_{\perp} = N \cdot \sin \alpha 
\end{cases}
\end{align*}
\]

(14)

We substitute the initial data in the form of the maximum effort into the resulting equation

\[N = 1,8 \div 2,0 \text{т} \quad \text{(15)}\]

and we also consider the slope of the trapezoidal tooth

\[\alpha = 45^\circ \quad \text{(16)}\]

\[
F = \frac{N(\cos \alpha + \mu \cdot \sin \alpha)}{\mu \cdot \cos \alpha + \sin \alpha} = \frac{2000 \cdot (\cos 45 + 0,03 \cdot \sin 45)}{0,03 \cdot \cos 45 + \sin 45} = 1883,5 \text{kg} \quad \text{(17)}
\]

Considering the design features, namely to ensure stability, we need 4 lobes and the force will be redistributed into 4 parts, we get:

\[P = 1883,5/4 = 470 \text{ kg} \quad \text{(approximately) load per lobe.} \quad \text{(18)}\]

We proceed to determine the exact geometric parameters, taking into account the maximum displacement (bending) of the plate \(\Delta \approx 2 \text{ мм}\).
formula for determining the maximum offset (bend) of the end of the plate.

\[ \Delta = \frac{P \cdot l^3}{3 \cdot E \cdot I} \]  

(18)

To facilitate calculations, we use Microsoft Excel. Using the selection method, we determine the length of the plate from the place of maximum compression with the nut – \( l = 75 \text{ mm} \), height – \( h = 10 \text{ mm} \) and width – \( b = 20 \text{ mm} \).

3. Experimental study

The tested design is a system of Layher core elements that has 2x2 cells in the plan and 1 cell in height (the cell has dimensions of 2x2x2).

Tests are performed on a vertical load that is concentrated on the middle post (vertical element). To transfer the load to the central post, an improvised mast with a traverse is assembled. Loading is performed using a hydraulic jack, which in turn is connected to a hydraulic compressor.

![Figure 5. Testing scheme](image)

Pre-tested compensator is mounted in a diagonal by means of welding. The condition for including a diagonal element in operation under a vertical load (the horizontal load on the system would imply the presence of additional detachments and auxiliary posts) is achieved by partially detaching the loaded post from the base of construction.

During testing, loading is performed step by step by components \( N = 1/10 \text{–} 1/20 \) from the design load. The tension characteristics are registered by strain gauges installed on the elements via an
automated block of hardware and software measurement tools. The calculated load is determined from the static calculation of the SYSTEM in the LIRA PC by step-by-step approximations until a system element with a compensator reaches a force exceeding -17.3 kN. Then we compare the theoretical values of the forces calculated in the LIRA PC and the experimental values obtained by conducting tests.

**Figure 6.** Comparison of forces
The compensator is triggered at a load of approximately 5000 kg, and the force in the D3 diagonal is -1730 kgs. After triggering, the force was approximately -1600 kgf, while the D2, D4 diagonals were additionally loaded and the D1 diagonal was uneloaded.

4. Conclusions
Arbitrary schemes have been studied, the use of compensating devices in which allows reducing the metal content of the structure by 20%. A compensating device was developed and calculated. An experiment was conducted to identify the redistribution of forces between elements when using compensating devices: the results generally coincide with the theoretical calculations.

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