Efforts redistribution in statically indeterminate bar systems based on scaffolding by force limiter

Khaidarov Lenar1[0000-0003-2662-6020], Shmelev Gennady1[0000-0001-6472-9413] and Salakhutdinov Marat1[0000-0002-9452-0271]

1Kazan State University of Architecture and Engineering, Kazan, Russia
E-mail: haidarov_lenar@mail.ru

Abstract. Scaffolding structures are commonly statically indeterminate and therefore the load-bearing capacity of the elements is not fully used, and the load-bearing capacity of the structure is limited by the most loaded element. It is important to redistribute the forces in the structure elements to make the most efficient use of their load-bearing capacity. It is suggested to introduce force limiters into the most loaded elements that allow shifts inside the element when the force limit value is reached. Due to this displacement the forces inside the element are reduced and redistributed to the adjacent elements. A numerical analysis has been carried out on the example of wall construction to assess the impact of the force limiter on the load-bearing capacity of the structure. The article presents the design of a force limiter designed for vertical diagonal. Laboratory test of the force limiter as part of scaffolding assembly was carried out.

Keywords: structures, modular scaffolding, temporary demountable structures, laboratory test.

1 Introduction
At present, temporary demountable structures from scaffolding are often used for a variety of functions at public and private events. They may provide viewing facilities, platforms and supports for performers, and for media facilities [1]. Various aspects of safe temporary structures discussed in [2-3]. Scaffolding structures are in most cases statically indeterminate systems. The limit state of these structures is determined by the limit state of the most loaded element, while the other elements of the system may have a reserve. In order to fully utilize the load-bearing capacity of the system, it is necessary to redistribute efforts from the most loaded elements to the less loaded ones. One of the ways to redistribute the forces is to allow shifting motion in element when its limit state is reached: shortening at compression, elongation at tension. It can be done with a force limiter.

2 Methods
2.1 Numerical study of force limiter behavior
To asses a force limiter behavior a bay with dimensions of 2×2 m from the common scaffolding system with a wedge connection is considered (figure 1). All elements are made of steel. The standards and ledgers have a tubular cross – section with a diameter of 48.3 mm and a wall thickness of 3.2 mm. The standard – ledger connection is semi–rigid and its behavior is nonlinear [4-6]. Diagonal has a tubular cross-section with a diameter of 48.3 mm and a wall thickness of 2.4 mm. The diagonal is installed with an eccentricity of 5 cm from the standard – ledger plane. The diagonal is modeled using travel spring with stiffness of 12 kN/cm [7-9].
The rigidity of the bay is primarily provided with the brace diagonal [10-14], so it is the first to reach the limit state at a load value of 6.25 kN. Load capability of the diagonal to the compressive force is 8.27 kN. The bending moment al ledger ends is 19 kN×cm, while load-bearing capacity of a ledger connection to the bending moment is 67.5 kN×cm, i.e., the ledger-standard connection is loaded only for 28% of the load-bearing capacity (figure 2).

We consider the behavior of the bay with force limiter in the diagonal. Behavior of a diagonal with the force limiter is presented in figure 3. Load capability of the diagonal to the compressive force (8.27 kN) is accepted as $N_{ult}$.

When the force of the limit value is reached in the diagonal, the element begins to deform freely at a constant value of force while the additional load is taken up by the ledger-standard connection. The load has been increased to 7.22 kN until the bending moment in ledger connection reaches the load–bearing capacity 67.5 kN×cm. The load-carrying capacity of the bay under shear load has increased to 16% in comparison with the previous scheme.
The behavior of wall construction with force limiter was considered. Scaffold based wall structures can be various in height and are used as supports for floodlights, loudspeakers, TV cameras, vision screens and press boxes [1]. Usually, such structures are covered with fabric material and, as the result, they take on wind loads [15-17]. Wind load is one of the main loads on such structures [18-20].

To estimate the effect of using force limiters in wall structures, a number of calculations have been made on the example of walls with one and two bay widths, and the height was taken equal to or slightly less than four times the width. The width of bays is accepted equal to 2.57 m, height – 2 m, 1.5 m and 1 m.

The ultimate horizontal uniform load on constructions from a condition of achievement of efforts in elements and connections or the top point displacement of limiting values was defined. The figure 5 shows the results of the calculation of one of the schemes with a width of $2.57 \times 2 = 5.14$ m and a height of $1.5 \times 13 = 19.5$ m.

![Figure 5](image)

**Figure 5.** Axial forces in vertical diagonals (a) without force limiter (b) with force limiter.
The results of calculation are presented in table 1.

Table 1. Calculation results.

| Cross frame sizes, m | Bay sizes, m | Load capability of diagonal brace to the compressive force, kN | Ultimate horizontal uniform load, kN/m without force limiter | Ultimate horizontal uniform load, kN/m with force limiter | Load capacity increasing, % |
|----------------------|--------------|-------------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------------------|-----------------------------|
| B 2.57 H 10          | b 2.57 h 2   | -6.8                                                       | 0.62                                                        | 0.75                                                      | 21                          |
| 2.57                  | 9 2.57 1.5   | -7.9                                                       | 0.89                                                        | 1.08                                                      | 21                          |
| 2.57                  | 10 2.57 1    | -9                                                         | 1.02                                                        | 1.21                                                      | 19                          |
| 5.14                  | 20 2.57 2    | -6.8                                                       | 0.56                                                        | 0.69                                                      | 23                          |
| 5.14                  | 19.5 2.57 1.5| -7.9                                                       | 0.75                                                        | 0.91                                                      | 21                          |
| 5.14                  | 20 2.57 1    | -9                                                         | 0.92                                                        | 1.13                                                      | 23                          |

According to the calculations force limiters in diagonals allow to increase the bearing capacity of wall structures up to 23%, so cross frames can be located at a greater distance from each other and the amount of elements can be reduced this way.

2.2 Force limiter design
The collet-type force limiter we have developed is presented in the figure 6. This force limiter includes a collet and a threaded sleeve, and the displacement required to unload the element is due to the collet tooth jumping over the bushing wave. Threading on the outer surface of the bushing is performed by ring waves (teeth), which may have sinusoidal or trapezoidal profiles with different angles of the sides. The height and pitch of the ring waves determine the force at which the collet teeth will jump and the value of the redistributed force. On the outer side of the collet there is a screw thread for an adjusting screw, the rotation of which makes it possible to regulate the force at which the teeth jump over the bushing thread, including the complete unloading of the element at disassembly.

![Force limiter](image)

Figure 6. Force limiter.

2.3 Experimental study of force limiter behavior
To study the force limiter behavior a standard fragment of four bays measuring 2×2×2 m from the system scaffolding with a wedge connection was assembled (figure 7). The load was transferred to the central standard without support jack. The force from the standard is transferred to the adjacent supports in the axes "A/2", "C/2", "B/1", "B/3" mainly by the diagonals D1-D4. A force limiter is
installed in the diagonal D3. When the force in the diagonal reaches the limit value, the force limiter will actuate and an enforce redistribution to the other diagonals D1, D2, D4 will occur. The vertical diagonal has a lower load-bearing capacity to the compressive force than to the tensile due to the instability, so the vertical diagonal D3 with the force limiter is set in the ascending direction to the central standard and compressed, the other diagonals D1, D2, D4 – in descending direction and tensioned.

Prior to the test, the operating force in the force limiter was adjusted with threaded rings and tested in a tensile testing machine. The operating force 16 kN is the experimentally defined load capability of diagonal to the compressive force taking into account a reliability factor of 1.3. The force limiter is inserted into the vertical diagonal instead of a pipe section closer to the end of the element (figure 8).

The central column was loaded by a hydraulic jack. The load value was measured by load cell. The forces in the diagonals D1-D4 were determined by strain gages installed on the surface of the tubular part in the middle section along the length of the element.
3 Results and discussion

Figure 10 shows the change of forces in the vertical diagonals during the test.

The jump of the teeth of the force limiter occurred at a compression force in the diagonal D3 equal to 17 kN under the load of 52 kN. After triggering the force was about 16 kN. The force limiter was triggered by a force of 17 kN instead of adjusted 16 kN due to the eccentricity in the vertical diagonal. Since diagonals D1 and D3 form one frame, the force was reduced in both diagonals and the force was redistributed to the vertical diagonals D2 and D4.

4 Conclusion

The load-bearing capacity of scaffolding structures can be used more effectively with the force limiters.

A numerical study was carried out on the example of the construction of the wall to assess the effect of force limiter. It’s been determined that force limiters can increase the bearing capacity of structures up to 23%. This means that cross frames can be located at a greater distance from each other and can potentially reduce the metal intensity of the wall construction.

The collet-type force limiter has been developed and tested as a part of scaffolding assembly. As a result of the experiment, efforts in the assembly elements were redistributed by the force limiter.
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