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The influence of repeated low-cycle loads on the stress-strain state of steel-reinforced concrete drainage gutters

Oleksandr Andriichuk*, Ivan Yasiuk, Olga Uzhegova, Serhii Uzhehov

Lutsk National Technical University, Lvivska 75, Lutsk 43018, Ukraine

Abstract

The paper presents the results of experimental studies on the effect of repeated low-cycle loading on the stress–strain state of steel fiber reinforced concrete gutters. A comparison was made between the effects of single and repeated loadings. Overall, the findings demonstrate that steel fiber reinforced concrete gutters have higher resistance to cyclic loading compared to single loading, and they better withstand repeated impacts without significant material failure.

Keywords: steel fiber; drainage gutter; stress–strain state; load-bearing capacity; strength; crack resistance

1. Introduction

In modern road construction and transport infrastructure, ensuring the reliability and durability of materials used in roadside drainage systems is of particular importance. One promising structural solution is steel fiber reinforced concrete (SFRC) gutters, which combine the high strength of the concrete matrix with the ability of steel fibers to effectively limit crack propagation and reduce deformations. Improvements in concrete matrix performance have also been demonstrated in earlier studies (Dovbenko et al. 2024). Despite the growing interest in this material, the influence of repeated low-cycle loading on the stress–strain state of SFRC gutters remains insufficiently studied, highlighting the need for further experimental and theoretical investigation.

In construction practice, steel fiber reinforced concrete is regarded as a modern composite material that combines the mechanical strength of concrete, including demonstrated fatigue resistance and the effects of hybrid fiber reinforcement (Drobyshynets et al. 2024; Dvorkin et al. 2021), with the structural rigidity and reinforcing capacity provided by steel fibers. The use of SFRC in structures subjected to dynamic or variable loading is particularly relevant due to its enhanced crack resistance and its ability to limit the development of local damage. The importance of understanding deformation behavior under repeated loading has also been emphasized in studies of reinforced concrete beams (Korniychuck et al. 2024). Drainage gutters, which are widely employed in transport infrastructure, belong to this category of structures.

Repeated low-cycle loads induced by traffic, temperature fluctuations, and other external factors can gradually reduce the load-bearing capacity and operational stability of gutters. The application of such loads leads to the accumulation of damage within the material, changes in its stress–strain state and deformation characteristics, as well as redistribution of internal stresses across the

* Corresponding author. Tel.: +380-50-674-9391.
E-mail address: aleklutsk@gmail.com

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cross-section. As a result, the service life of SFRC gutters under real operating conditions is reduced. The structural response of fiber-reinforced elements under bending and deformation has been examined in several studies (Babych et al. 2019; Andriichuk et al. 2018; Babych et al. 2019). Modelling approaches have been proposed to describe deformation mechanisms in fiber-reinforced concrete (Kochkarev et al. 2018; Kochkarev et al. 2023), while experimental investigations have demonstrated that both fiber geometry and fiber type significantly influence strength and mechanical properties (Oliveira et al. 2018; Christ et al. 2024).

Previous studies focusing specifically on SFRC drainage trays and pipes have demonstrated their effectiveness under repeated loading, as well as characteristic crack development patterns (Andriichuk et al. 2017). Subsequent research confirmed the load-bearing capacity and deformation behavior of SFRC gutters and proposed numerical modelling approaches for predicting their structural performance (Andriichuk et al. 2021). Additional experimental investigations of annular SFRC elements under single loading conditions further support the material's resistance to deformation (Babych et al. 2017).

The aim of this study is to determine the influence of repeated low-cycle loading on the performance of SFRC drainage gutters.

Nomenclature

t	wall thickness of the SFRC gutter
l	length of the SFRC gutter
μ	steel fiber reinforcement ratio
w_k	crack width
F	applied load
η	applied load level
Δl	cross-section displacement of the gutter

2. Methods of experimental research

For the experimental investigation, three SFRC gutters of series 1SFRC (tested under single loading) and three gutters of series 2SFRCr (tested under repeated loading, where the index *r* denotes repeated loading) were manufactured. Each gutter had an internal diameter of Ø300 mm, a wall thickness of t = 40 mm and a length of l = 300 mm. Reinforcement was provided by hooked steel fibers (Ø0.8 mm, length l = 50 mm) with a reinforcement ratio of $\mu \approx 2\%$. Detailed information on structural solutions, manufacturing procedures, and the experimental methodology is provided in the studies by Andriichuk et al. (2017), Andriichuk et al. (2021), and Babych et al. (2017).

Figure 1 illustrates the commonly used scheme of crack distribution in gutters (a), cross-section displacement (b), and the bending moment diagram (c) during testing.

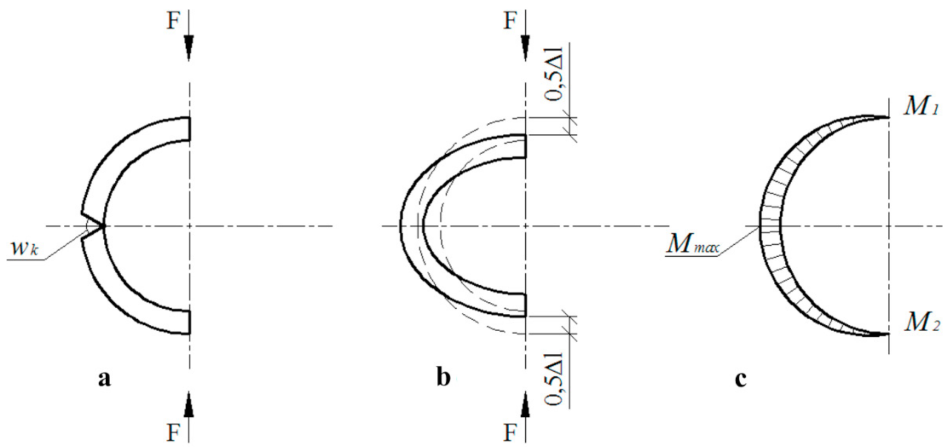

Fig. 1. (a) scheme of crack distribution; (b) cross-section displacement and (c) bending moment diagram in the gutters during testing

During the experimental testing of the SFRC gutters, the applied force was introduced as a concentrated load through a steel loading beam. The lower part of the specimen rested on a rigid base with a rubber layer. The tests were carried out using a PSU-125 hydraulic press. To improve the accuracy of load measurement, a calibrated reference dynamometer was used, allowing the applied load to be recorded with an accuracy of 50 N. In this setup, the load was applied by a hydraulic jack. The general view of the drainage gutter test is shown in Fig. 2.

Fig. 2. General view of the drainage gutter test. (a) steel loading beam; (b) tested drainage gutter; (c) fixed support; (d) hydraulic jack; (e) reference dynamometer; (f) upper plate of the PSU-125 press; (g) lower plate of the PSU-125 press; (h) displacement sensor and (i) displacement rod

Three specimens of series 1SFRC were loaded in increments averaging 8–12% of the ultimate load, while three specimens of series 2SFRCr were subjected to ten loading cycles with increments up to a load level of η = 0.6 of the ultimate load. During the 11th cycle, they were brought to failure (Fig. 3).

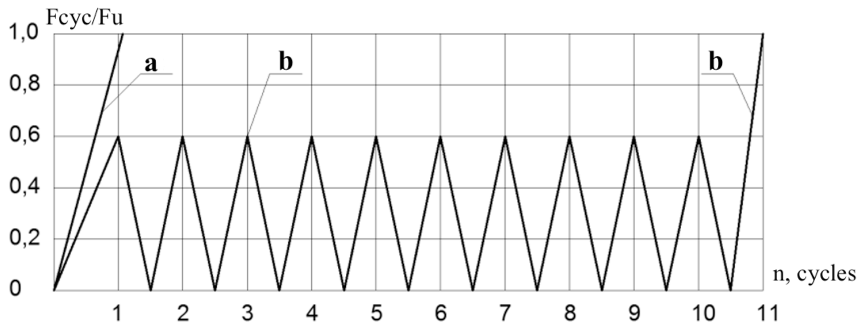

Fig. 3. Loading conditions of the tested drainage gutters: (a) single loading to failure and (b) repeated loading, cycles 1–11

During the experimental investigation of the influence of repeated loading (η = 0.6) on the stress–strain state of the SFRC gutters, each loading cycle was applied in six increments (approximately F = 1.56 kN per increment). Unloading during the cycles was performed using the same increments as during loading.

During the 11th cycle, the tested SFRC gutter specimens were brought to failure.

After each loading increment, a holding period of 5–7 minutes was maintained, during which readings from the dial indicators, measurements from the strain gauge system, and crack width values (w_k) were recorded. Displacements of the gutter wall caused by the applied load were measured using YCH-10 NM dial indicators with a resolution of 0.01 mm. Crack widths were measured using an MPB-2 microscope with a resolution of 0.05 mm. To measure strains in the concrete and SFRC material, strain gauges with a gauge length of 50 mm were bonded to the inner and outer surfaces of the gutter. The strain gauges were installed in pairs in two zones on both the inner and outer sides.

Results and discussion

The general view of the tested specimens after completion of the experiments is presented in Fig. 4.

Fig. 4. Tested specimens after the experiments: (a) 1SFRC and (b) 2SFRCr

During the experimental investigation of single loading to failure, the deformation characteristics of the SFRC gutters of series 1SFRC were determined.

Cross-section displacement (Δl). From the beginning of loading, the cross-section displacement (Δl) in the 1SFRC specimens increased proportionally to the applied load up to F = 3.33 kN. Beyond this level, plastic deformations began to develop, leading to a loss of proportionality between load and displacement. This behavior is illustrated in Fig. 5, where the averaged displacement values at different loading stages are presented for each specimen. The maximum displacement was recorded at F = 15.83 kN and reached 1.40 mm.

Crack formation (w_k). The first visible cracks in the 1SFRC specimens appeared suddenly in the zone of maximum bending moment at a load close to the ultimate value (F = 14.17 kN). At this stage, the crack width was w_k = 0.20 mm. When the load reached F = 15.0 kN, the crack width increased to w_k = 0.28 mm. The cracks exhibited a non-linear propagation pattern. Further increase in load up to F = 15.83 kN led to failure, as the cracks reached critical dimensions.

Deformations and cracking. The deformation and crack formation process was accompanied by the development of significant plastic deformations. As shown in Fig. 4, after completion of the test, the 1SFRC specimen exhibited substantial damage. The cracks that developed affected the overall condition of the element to such an extent that it could no longer sustain further increases in load. This behavior indicates the end of the plastic deformation stage and the onset of structural failure.

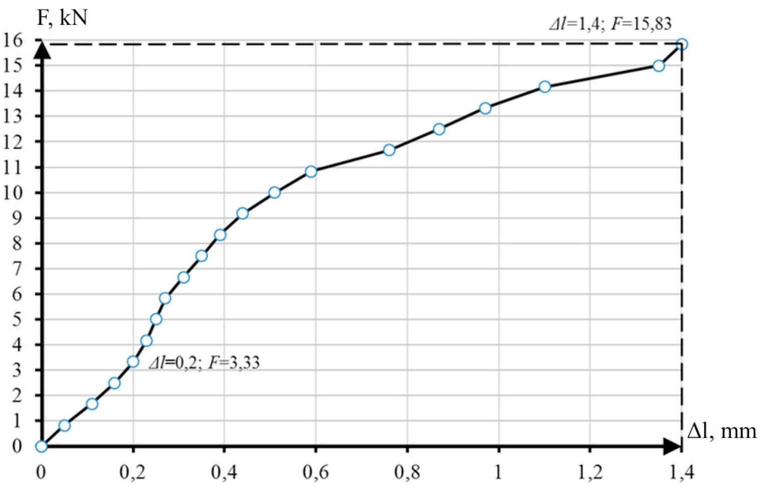

Fig. 5. Averaged cross-section displacements of the 1SFRC specimens

During the experimental investigation of repeated loading, the deformation characteristics of the SFRC gutters of series 2SFRCr were determined.

Cross-section displacement (Δl). In the first loading cycle, the maximum displacement reached Δl = 0.47 mm at F = 9.33 kN. By the 10th cycle, the cross-section displacement increased to Δl = 0.98 mm under the same load level. During the 11th cycle, at the maximum load of F = 10.83 kN, the displacement of the gutter walls reached Δl = 1.29 mm, after which the specimens failed (Fig. 6).

Crack formation (w_k). The first cracks in the SFRC specimens appeared during the 10th loading cycle at a load of F = 9.33 kN, with an initial crack width of w_k = 0.05 mm. In the 11th cycle, at the same load level (F = 9.33 kN), the crack width increased to w_k = 0.1 mm. Beyond this point, the gutters were unable to sustain further loading and failed.

Deformations and cracking. During the initial loading cycles (cycles 1–9), the specimen deformations were minor and exhibited a linear dependence on applied load. A pronounced increase in crack width and crack density was observed during the final loading cycles, indicating progressive material degradation and confirming the ability of SFRC gutters to withstand loading up to critical levels.

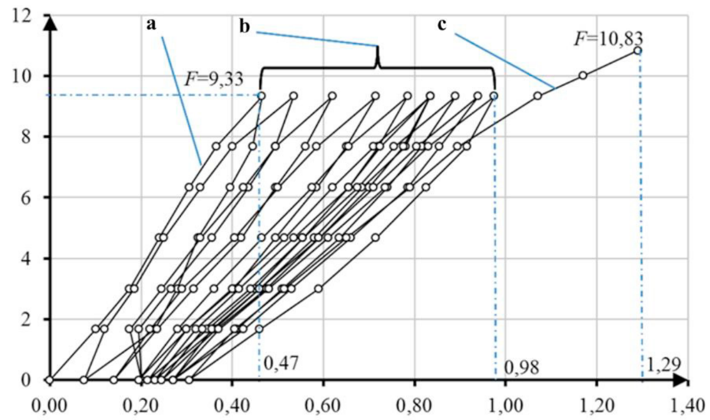

Fig. 6. Averaged cross-section displacements of the 2SFRCr specimens: (a) during the first cycle; (b) during cycles 2–10 and (c) during the 11th cycle

The main objective of the investigation of SFRC gutters is to compare their strength characteristics during the 11th loading cycle with those obtained under single loading to failure.

A comparison of the deformation values recorded during repeated loading (11th cycle) and during single loading to failure shows an increase in deformation by a factor of 2.19 to 3.73 (Fig. 7).

During the 11th loading cycle, a gradual increase in deformation is observed, indicating the accumulation of material degradation under repeated load application. Although failure does not occur immediately, the deformation continues to increase. The maximum deformation recorded after the 11th cycle reached Δl = 1.29 mm at the maximum load F = 10.83 kN.

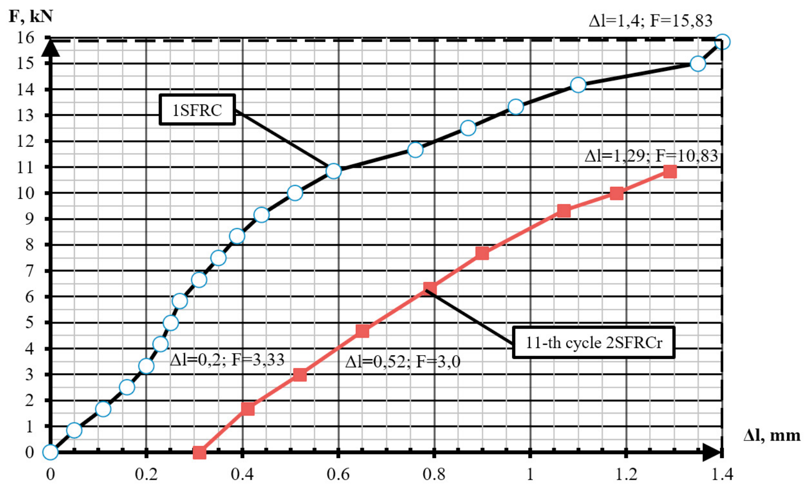

Fig. 7. Averaged cross-section displacements of the 1SFRC and 2SFRCr specimens

Under single loading, the gutters exhibit smaller deformations compared to repeated loading. For example, at a load of F = 10.83 kN, the deformation reaches Δl = 0.59 mm, which is lower than under repeated loading (Δl = 1.29 mm). This difference may be attributed to the fact that single loading does not allow the material to accumulate progressive changes.

4. Conclusions

1. The investigation of the stress-strain state of SFRC gutters demonstrated that they exhibit high stiffness and crack resistance under repeated low-cycle loading. Deformations in the initial loading cycles were minimal and increased significantly only in the later cycles, confirming the high effectiveness of SFRC as a structural material for drainage gutters.
2. A comparison of deformation values obtained under single loading to failure and during repeated loading (11th cycle) shows an increase in deformation by a factor of 2 to 3.7.
3. SFRC gutters demonstrate high resistance to repeated low-cycle loading, which makes steel fiber reinforced concrete a promising material for application in road and hydraulic engineering structures.

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