Experimental Investigation of the Load Carrying Capacity of Eccentrically Loaded Reinforced Concrete Elements Strengthened with CFRP

Mykolas Daugevičius*, Juozas Valivonis, Artūras Beinaravičius, Tomas Skuturna, Marius Budvytis

Department of Reinforced Concrete and Masonry Structures, Vilnius Gediminas Technical University, Saulėtekio Ave. 11, LT-10223 Vilnius, Lithuania

Abstract

The article analyses the behavior of eccentrically loaded confined rectangular cross section reinforced concrete elements. Fourteen elements were tested, 6 of which were strengthened with carbon fiber reinforced polymer. The influence of the eccentricity of vertical loading on the behavior of strengthened and non-strengthened elements was investigated. It was experimentally determined that the influence of concrete confinement decreases when loading eccentricity increases. It is necessary to take into account the decrease of the confined concrete strength when the load carrying capacity of eccentrically loaded element is evaluated.

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Keywords: eccentrically loaded, concrete confinement, confined concrete strength, load carrying capacity, brittle failure.

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| \( e \) | eccentricity                 |
| \( f_c \) | compressive strength of plane concrete |
| \( f_{cc} \) | compressive strength of confined concrete |
| \( h \) | height of cross section      |

Greek symbols

| Symbol | Description                  |
|--------|------------------------------|
| \( \varepsilon_c \) | compression strains          |
| \( \varepsilon_t \) | tensile strains              |

1. Introduction

The existing compressed elements in reinforced concrete structures generally are not only compressed but also additionally affected by bending moments and shear forces. According to design recommendations, when eccentrically loaded concrete elements are designed, it is necessary to evaluate the increase of the loading eccentricity during the element service time, wherefore tensile stresses can occur in a part of cross section and necessitate additional reinforcement. If this effect is not evaluated, then the load carrying capacity of an eccentrically loaded element can be insufficient. In this case the element should be strengthened. Our practice of strengthening elements in structures shows that a simple strengthening can...
be accomplished by confinement of carbon fiber reinforced polymers. Various studies of confined concrete show that compressive strength of concrete increases and the increment of strength depends on the cross section of the element. Consequently, in design of eccentrically loaded confined concrete elements the strength of confined concrete is used. In this case, the dominance of the confined concrete strength over the design of the element load carrying capacity decreases.

Analysis of experimental and numerical results of circular cross sections elements loaded with eccentric load and confined with CFRP accomplished by [1–2] shows that numerical methods overestimate the load carrying capacity. Experimental researches proved that when the ordinary concrete strength reaches 100 MPa, confinement provided by CFRP is inconsiderable [3–5]. In assessing the magnitude of eccentricity, the research of [6] shows that the influence of confinement increases with increasing force eccentricity. Although compressive strength of centrically loaded circular cross section elements confined with CFRP increases mostly, but under eccentric load their load carrying capacity decreases most of all in comparison with rectangular cross section elements where considerable decrease is not realized [7].

Experimental researches [7] showed that confinement of concrete with CFRP has the greatest impact when crushing of concrete in the compressed cross section area occurs. This can be explained by an increase of confined concrete strength. Increase of confined concrete strength has less influence if failure occurs in the tensioned cross section part. If strengthening is accomplished not only with the help of confinement provided by CFRP, but also by the longitudinally strengthened tensioned part with CFRP, then the eccentric compression bearing capacity of a reinforced concrete element when e/h = 0.1 can be increased up to 30 % [8].

Finite element analysis of an eccentrically loaded reinforced concrete element strengthened with CFRP shows that the maximal value of compressed concrete stresses is independent of e/h ratio and a perfect bond between concrete and CFRP can be used [9]. Studies of a rectangular reinforced concrete element strengthened with CFRP and subjected to eccentric load show than when e/h ratio reaches 0.86, the influence of confinement provided by CFRP disappears [10].

In design of the load carrying capacity of such elements, the diagram of compressed concrete can be divided into two parts: rectangular or trapezoidal [10] or just rectangular [9]. In each case, if curvilinear distribution is changed into trapezoidal or rectangular one, then additional coefficients which correct compressive stresses and the position of a neutral axis are used [9–11], and they depend on the compressive concrete strength, deformations, but do not depend on the load eccentricity. When distribution diagrams of trapezoidal and rectangular stresses are used, then the state of stresses is similar to that of the layered elements. If only a rectangular diagram is used, then it is not evident which strength, confined concrete or ordinary concrete, have more influence on the load carrying capacity. So in this work an analysis of the experimental results of reinforced concrete and reinforced concrete confined with CFRP behavior under eccentric load action was accomplished in order to determine the influence of confined or ordinary concrete on the load carrying capacity.

Table 1. Characteristics of experimental samples

| Sample name | Characteristic of sample | Eccentricity, m | Cross section |
|-------------|--------------------------|----------------|---------------|
| K1          | Concrete                 | 0.0            |               |
| K2          | Concrete                 | 0.03           |               |
| K3          | Concrete                 | 0.045          |               |
| K4          | Reinforced concrete      | 0.0            |               |
| K5          | Reinforced concrete      | 0.03           |               |
| K6          | Reinforced concrete      | 0.045          |               |
| K7          | Reinforced concrete      | 0.0            |               |
| K8          | Reinforced concrete      | 0.03           |               |
| K9          | Reinforced concrete      | 0.045          |               |
| K10         | Reinforced concrete      | 0.0            |               |
| K11         | Reinforced concrete      | 0.03           |               |
| K12         | Reinforced concrete      | 0.045          |               |
| K13         | Reinforced concrete      | 0.0            |               |
| K14         | Reinforced concrete      | 0.03           |               |
| K15         | Reinforced concrete      | 0.045          |               |
2. Experimental program

Reinforced concrete and strengthened elements prepared for experimental research had the same rectangular cross section. A total of 14 elements were prepared and tested, 6 of which were wrapped with carbon fibre reinforced polymer. The height of all elements was 625 mm. Characteristics of each elements and external load eccentricity are presented in Table 1. Eccentricity (e) and height (h) ratio e/h of eccentrically loaded elements were 0.2 and 0.3. All elements were made from the same concrete batch and concrete compressive strength was 26.3 MPa and deformation modulus 26.4 GPa. Yielding stresses of longitudinal internal reinforcement steel bars was 561.8 MPa. For confinement of reinforced concrete elements carbon fiber windings were used. Longitudinal tensile strength of carbon fibers tape was 4800 MPa. Elements K9…K14 were wrapped with 1 layer of carbon fiber reinforced polymer. To prevent premature failure of the elements, their ends were additionally wrapped with one 100 mm wide layer of carbon fiber.

The external load was transferred through the steel hoods at which the steel hinges were attached. The loading scheme is presented in Fig. 1. When elements were loaded centrically, the external load was transferred through the whole cross section without using any steel hoods.

![Fig. 1. Loading scheme and arrangement of measuring devices](image)

During the loading deformations were measured at the most tensioned and compressed external layers. Deformations at the longitudinal steel reinforcement were measured too (Fig. 1). The measuring base was equal to 200 mm. Additional electric gauges, which were glued through section height, were used.

3. Analysis of experimental results

Confinement of a compressed reinforced concrete element with CFRP allows restraining of lateral deformations. Respectively, it increases ultimate longitudinal deformations and increases compressive resistance. In order to determine ultimate deformations in non-strengthened elements, concrete and reinforced concrete elements were centrically loaded. The comparison of longitudinal deformations is presented in Fig. 2. Longitudinal deformations of strengthened elements at the load level when the ultimate load of ordinary concrete elements is reached are approximately 18.5% smaller. The ultimate axial deformation is approximately 481% higher and the ultimate axial deformation of reinforced concrete samples was just 15% higher in ordinary concrete samples. The load carrying capacity of a reinforced concrete element and confined elements were 25% and 103% higher than in ordinary concrete samples. The failure of axially loaded elements was characterized by concrete crushing.

Tensile stresses developed in eccentrically loaded reinforced and strengthened reinforced concrete elements. The magnitude of tensile and compression stresses and the position of neutral axis depended on the eccentricity of vertical load. Deformations in the mostly compressed part of the section of reinforced concrete and strengthened elements when the ratio e/h = 0.2 were 36% and 40% higher than in centrically loaded samples with the same characteristics. The comparison of deformations and the position of the neutral axis at the load level which corresponded to the carrying capacity of elements...
K5 and K6 showed that confinement has no influence on the magnitude of stresses and the neutral axis position. Therefore, it is rational to use prestressed carbon fibers yarns. Distribution of tensile and compression stresses shows that the most part of cross section is compressed and the strength of tensile steel bars in reinforced concrete elements is not used because tensile stresses approximately reached 3 MPa. Whereas strengthened elements K11 and K12 according to provided CFRP confinement can resist higher load and at a higher load level the compressed part of the cross section decreases and tensile strength of steel bars is used more as tensile stresses reached approximately 116 MPa. The manner of the failure of eccentrically loaded reinforced concrete (K5, K6) elements and strengthened elements (K11, K12) when the ratio $e/h = 0.2$ was the same. Failure occurred in the mostly compressed concrete part, and the load carrying capacity of this elements depended on the compressive concrete strength.

Increasing of vertical load eccentricity shows that the load carrying capacity decreases. When the ratio $e/h = 0.3$, the influence of confined compressed concrete strength decreases (Fig. 3) and the increase of the load carrying capacity is lower (Fig. 4). Although the influence of confinement in the circular cross section elements [6] increased with increasing load eccentricity, in this research – on the contrary, it decreased. This can be explained by different reinforcement ratios, concrete strength and the amount of CFRP layers. The load carrying capacity of strengthened elements when ratios $e/h = 0.2$ and $e/h = 0.3$ decreased by 50% and 64% in comparison with centrically loaded strengthened elements. Deformations in the mostly compressed part of the section of reinforced concrete elements were almost equal to the centrically loaded elements of the same characteristics. But in strengthened elements (K13, K14) deformations were 35% lower than in the centrically loaded samples of the same characteristics.

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The experimental load carrying capacity values of each sample are presented in Table 2. With increase of load eccentricity, the carrying capacity of reinforced concrete elements and the strengthened reinforced concrete elements decreases. But the value of the decrease of the load carrying capacity differs. When eccentricity increased from 0 to 0.03 m or to 0.045 m, then the load carrying capacity of reinforced concrete elements decreased by 43% and 56%. Therefore, the load carrying capacity of strengthened reinforced concrete elements decreased by 50% and 64%. But the load carrying capacity of strengthened elements when the ratio e/h = 0.2 and 0.3 increased by 43.3% and 32% in comparison with non-strengthened elements.

Table 2. Load carrying capacity of tested elements

| Sample name | Eccentricity, m | Maximal load, kN | Failure characteristic               |
|-------------|-----------------|------------------|--------------------------------------|
| K1          | 0.0             | 493              | Crushed concrete                     |
| K2          | 0.0             | 432              |                                       |
| K3          | 0.0             | 510              | Crushed concrete, buckled steel bars |
| K4          | 0.0             | 597              | Crushed concrete, buckled steel bars |
| K5          | 0.03            | 380              | Crushed concrete, buckled steel bars |
| K6          | 0.03            | 297              | Crushed concrete                      |
| K7          | 0.045           | 96               | Crushed concrete at the attached load place |
| K8          | 0.045           | 264              | Crushed concrete, buckled steel bars |
| K9          | 0.0             | 908              | Brittle concrete failure after CFRP rupture |
| K10         | 0.0             | 1036             |                                      |
| K11         | 0.03            | 472              | Crushed concrete at the mostly compressed section |
| K12         | 0.03            | 498              |                                      |
| K13         | 0.045           | 356              | Crushed concrete at the attached load place. Tensioned steel bars yielding |
| K14         | 0.045           | 341              |                                      |

4. Conclusions

Confinement of a compressed reinforced concrete element with CFRP allows restraining of lateral deformations. Respectively, it increases ultimate longitudinal deformations and increases compressive resistance.

Accomplished experimental research showed that the ultimate axial deformation in centrically loaded strengthened elements increased up to 481% in comparison with ordinary concrete elements. Such increase of deformation was governed by provided confinement with CFRP. Deformations in the mostly compressed part of the section of reinforced concrete and strengthened elements when the ratio e/h = 0.2 were 36% and 40% higher than in centrically loaded samples with the same
characteristics. But when the ratio $e/h = 0.3$, deformations were 35% lower than in the centrically loaded samples of the same characteristics.

The load carrying capacity of a reinforced concrete element and confined elements were 25% and 103% higher than in ordinary concrete samples. With the increase of external load eccentricity, the load carrying capacity of tested elements decreased. When eccentricity increased from 0 to 0.03 m or to 0.045 m, then the load carrying capacity of strengthened reinforced concrete elements decreased by 50% and 64%. But the load carrying capacity of strengthened elements when ratio $e/h = 0.2$ and 0.3 increased by 43.3% and 32 % in comparison with non-strengthened elements.

Comparison of deformations and position of the neutral axis showed that confinement has no influence on the magnitude of stresses and the position of the neutral axis when the load which corresponds to the load carrying capacity of a non-strengthened element is reached. When the ratio $e/h$ was 0.2, the load carrying capacity of strengthened elements mostly depended on the confined concrete compressive strength. With increasing eccentricity of the load, the influence of the confined concrete compressive strength on the load carrying capacity decreases. When the ratio $e/h$ was 0.3, the load carrying capacity of strengthened elements mostly depended on the ordinary concrete compressive strength and tensile steel bars.

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