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AN EXPERIMENTAL STUDY ON THE STRUCTURAL PERFORMANCE OF REINFORCED CONCRETE LOW-RISE BUILDING COLUMNS SUBJECTED TO AXIAL LOADING

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Abstract

It has been commonly recognized by the international research and practice community that the presence of both outer and inner stirrups may significantly enhance the axial load capacity of reinforced concrete (RC) columns. However, there is limited testing evidence to support this conclusion that has been published nationally. This paper reports an experimental programme to study the effectiveness of stirrup detailing on the structural performance of columns having small sectional dimensions that are common in low-rise building structures. Nine column specimens with the same geometrical dimensions of 220 mm × 220 mm × 880 mm in three batches were detailed with different stirrup categories, have been gradually axially loaded to failure. The test data have revealed that although the presence of stirrups can generally enhance the axial load capacity of the column specimens, the enhancing levels are much dependent to the shapes of the stirrups. Selected interesting aspects of the test results have also been discussed, which set a concrete base for recommendations for design and detailing of such vertical structural elements.

Keywords: experimental investigation; low-rise building columns; axial load capacity; stirrups.

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1. Introduction

Reinforced concrete columns are often detailed with outer stirrups that tie together all longitudinal rebars and inner ones tying some of the rebars along the column sectional dimensions. The common shapes of inner stirrups are either cross-link or diamond shapes. Stirrup detailing serves for two purposes. The first is to keep column longitudinal rebars align with the formwork and stable during the concreting process. Along the column height, closed outer stirrups should be placed at a spacing less than a codified value [1]. Meanwhile, providing inner stirrups is optional unless the column cross-section is long-narrow rectangular. The second purpose is to improve the axial load capacity by confining concrete material and preventing the rebars from buckling. Previous researches have shown that if a column is properly detailed, confinement effects could increase the concrete strength as high as 40% [2]. Also, it can be expected that closer-spacing stirrups could reduce the buckling length of

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rebars so that they can share more compressive stress with the concrete core at the pre-failure stage of a column.

Although the enhancement effects by column stirrups on the axial load capacity are well supported by previous theoretical prediction [2], the applicability of such enhancement in design practice is very limited, particularly for columns with small sectional dimensions in low-rise building structures. The limited applicability can partly be explained by the lack of the experimental data for such small column sizes. Furthermore, the guidelines for evaluating the effects in the current Vietnamese code of practice are not so informative. For the demand for column axial load capacity is getting higher and higher in modern buildings nowadays due to more stringent architect requirements for column sectional sizes, such enhancement, if significant, should be taken into account.

This paper reports a series of tests to examine the effectiveness of stirrups on enhancing the axial load capacity of RC columns. Nine column specimens whose cross-sectional dimensions were extracted from typical low-rise building structures were detailed and constructed with different stirrup detailings that consist of inner and outer stirrups were axially loaded statically to failure. The test results including the load-displacement curves and failure modes will be discussed to clarify the contribution of stirrups to the overall structural performance of the test structures. Based on the discussions, some recommendations for design, analysis and construction of low-rise building columns are also addressed.

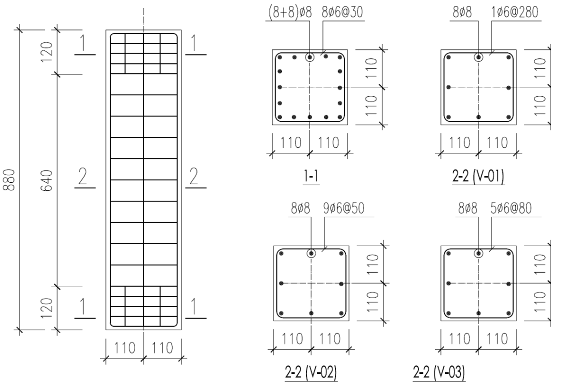
2. Experimental programme

2.1. Design and detail of test specimens

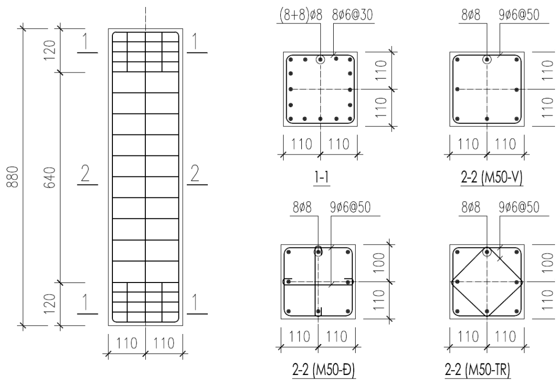
The cross-section of test specimens is selected to be 220 mm × 220 mm, that is the typical size of columns in low-rise buildings in North Vietnam. The specimen height is 880 mm equal to four times the width of its section to satisfy the basic requirement for this type of testing units. All test specimens were detailed constructed with concrete material and stirrup detailing which are the same as actual building structures. Meanwhile, due to the capacity of the compressing machine used for this investigation, the diameter of longitudinal reinforcing bars in all specimens is selected to be 8 mm, much smaller than those in the actual building columns, which are rarely smaller than 14 mm. The use of small diameter for rebars here can be acceptable since the main objectives of the experiments focus on the contribution of stirrup detailing, not that of the rebars, to the structural performance of the columns specimens.

Nine specimens were divided in three groups; each group has its own testing objective. Figs. 1(a), 1(b), and 1(c) show design of the specimens. The first group (Fig. 1(a)) was aimed to examine the effectiveness of outer stirrups in confining concrete. The test specimens, namely V-01, 02 and 03, were reinforced with outer stirrups 6 mm in diameter with spacings of 280 mm (V-01), 50 mm (V-02) and 80 mm (V-03). In Group 2 (Fig. 1(b)), three specimens were reinforced with three different stirrup configurations at the same spacing of 50 mm. The stirrup configurations are: (i) only outer stirrups in Specimen M50-V; (ii) Outer stirrups together with cross ties in Specimen M50-Đ, (iii) Outer stirrups together with inner diamond stirrups in Specimen M50-TR. Similarly, specimens in Groups 3 were reinforced with the same configurations at a spacing of 80 mm. Detail of specimens in this group are shown in Fig. 1(c).

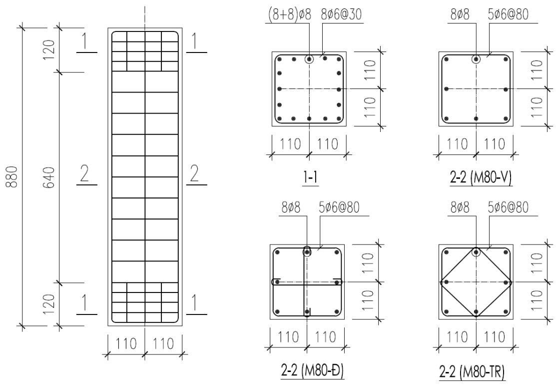
To prevent any local damage when being subjected to the compressive forces, both ends of the specimens are strengthened with a double value of the common reinforcement ratios as shown in Section 1-1 in Figs. 1(a), 1(b), and 1(c). Fig. 2 presents a photo of the reinforcement cage of each type of specimens before the concreting process.



(a) Group 1: Outer stirrups at spacings of 50/80/280



(b) Group 2: Mixed stirrups at a spacing of 50 mm



(c) Group 3: Mixed stirrups at a spacing of 80 mm

Figure 1. Reinforcement detail of test specimens

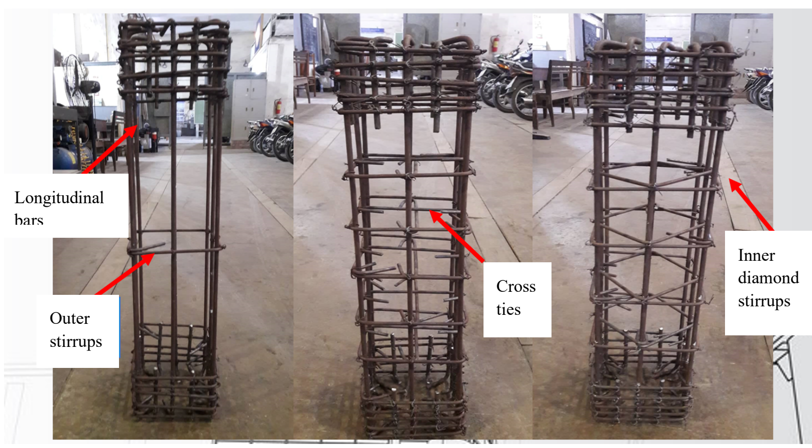


Figure 2. A photo of reinforcement cages of test specimens

Both longitudinal reinforcing bars with a diameter of 8 mm and stirrups with a diameter of 6 mm used in this experimental programme was the same steel grade CB240-T, whose yield strength of 240 N/mm^2. It is emphasized that three specimens in each group were cast with the same concrete batch. The equivalent cylinder compressive strength for specimen groups 1, 2, and 3 were 20.3 MPa, 25.2 MPa, 26.9 MPa, respectively.

2.2. *Test setup and instrumentations*

Fig. 3(a) shows a side view of the test setup. The specimens were axially loaded by a compression table with 500-Ton capacity. The testing force was measured by a load cell placed on top of specimens. To extract the compressive strain, three Linear Variable Differential Transformers (LVDT) with 50 mm stroke were attached on three out of four specimen faces, each LVDT was used to measure the relative displacement at two sections separated 150 mm as shown. The compressive strain was calculated as follows:

$$\varepsilon_{comp.} = \frac{1}{3}\left(\frac{f_1}{150} + \frac{f_2}{150} + \frac{f_3}{150}\right) \tag{1}$$

where $\varepsilon_{comp.}$ is the average compressive strain of the test specimen; and f_1, f_2, and f_3 are the relative displacements measured at three faces of the specimen.

All test data were recorded by a data-logger with 30 channels (Fig. 3(a)). Fig. 3(b) provides a closer look on the test setup. Both ends of each specimen was capped by a couple of steel cages 5 mm thickness to make sure there is no local damage during the test run.

(a) A photo of a side view

(b) A photo of a closer look

Figure 3. Detail of the test setup

The test specimens were gradually loaded to the failure point which was signed by a sudden decrease of the acting force due to the force-controlled procedure. After the applied load was gradually decreased to zero, the same procedure was repeated to confirm the peak axial load.

2.3. Failure modes of test specimens

The typical failure mode of test specimens was the crushing of concrete combined with buckling of longitudinal reinforcing bars which mainly occurred at the middle-section of every specimen. The failure was initiated with diagonal/horizontal cracks at one or more faces of specimens, that were gradually and progressively spread to the other faces (Fig. 4(a)). With a small increase of applied load, concrete cover started spalling (Fig. 4(b)), which was immediately followed by buckling of longitudinal bars and heavy concrete crushing as shown in Fig. 4(c). This failure mode, concrete crushing combined with rebar buckling, is well consistent with previous seismic tests on V-shape columns [3, 4] and other types of RC structures [5–10]. It worth-noting that at the final failure stage, both ends of most test specimens were intact.

(a) Onset of failure

(b) Concrete spalling

(c) Buckling of longitudinal bars and concrete crushing

Figure 4. Failure mode of test specimens

3. Discussions

The stress-strain curves of test specimens presented in this section were constructed with the horizontal axis describing the relative compressive strain $\varepsilon_{comp.}$ calculated by Eq. (1). The vertical axis describes the compressive stress given by:

$$\sigma_{comp.} = P/A_{gross} \tag{2}$$

where P is the compressive force acting on the specimens; and A_{gross} = 220 mm × 220 mm is the area of the specimen gross section.

Since the specimens were repeatedly loaded to confirm the peak axial load value, the original stress-strain curves had several repeated ascending and descending branches as shown in Fig. 5. In the following discussions, these repeated segments have been omitted to make the curves clearer.

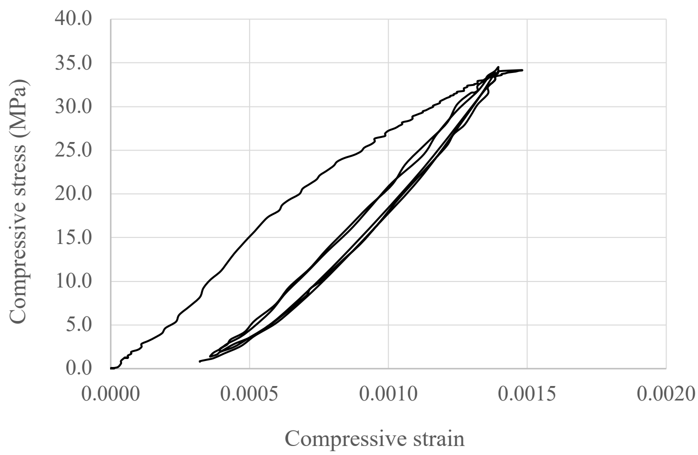


Figure 5. The original stress-strain relationships of Specimens M80-TR

3.1. Enhancement on the concrete stress strain curve by the outer stirrups

Fig. 6 compares the stress-strain curves of three specimens in Group 1 whose outer stirrup spacings are respectively 280 mm for Specimen V-1, 50 mm for Specimen V-2, and 80 mm for Specimen V-3. As can be seen, the ascending and descending parts before and after reaching the peak point of these stress-strain relationships are pretty similar regarding to the curve tendency. In particular, the descending parts of Curve V-1 and V-3 are almost identical. In terms of compressive stress, the peak value in Test V-2 with the closest spacing of 50 mm expectedly reached the highest peak, that is 33.6 MPa, followed by the peak value of 26.5 MPa in Test V-3 with a spacing of 80 mm, and then 22.8 MPa in Test V-1 where the specimen was reinforced with stirrup spacing of 280. However, the increasing in the peak compressive stress is generally lower and not proportional to the increasing in the stirrup amount used in the specimens. As can be seen in Table 1, the ratios of the peak stress values between specimens V-3 and V-1 (V-2 and V-3) are 1.16 (1.26), while the ratios of the stirrup amount are 3.50 (1.60), respectively.

3.2. Enhancement of the internal diamond-shaped stirrups

Effectiveness of diamond-shaped stirrups can be evaluated by comparing specimens with and without this type of internal stirrups which should be cast with the same concrete batches and detailed with the same stirrup spacings. Figs. 7(a) and 7(b) compares the stress-strain curves of such specimens reinforced with stirrups at a spacing of 80 (mm) in Group 3 and at a spacing of 50 (mm) in Groups 2. As can be seen in Fig. 7(a), the peak axial stress of Specimen M80-V (without diamond

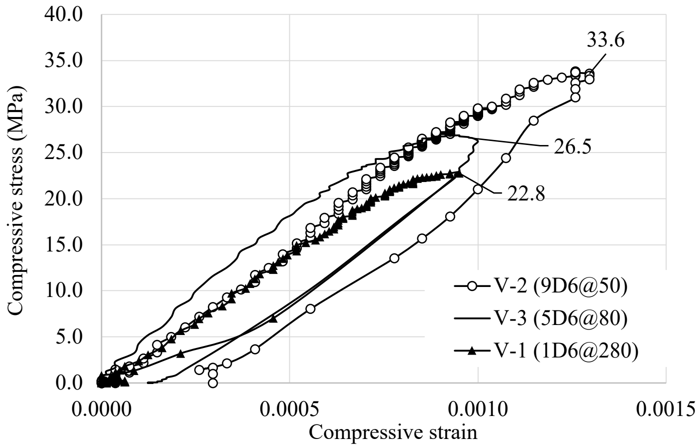


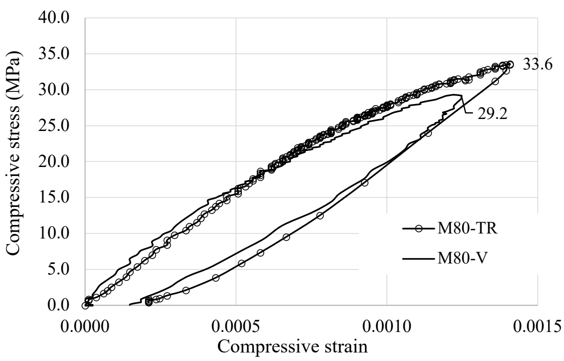
Figure 6. Stress-strain relationships of the specimens in Group 1

Table 1. The ratios of stirrup amounts and the peak values of compressive stress

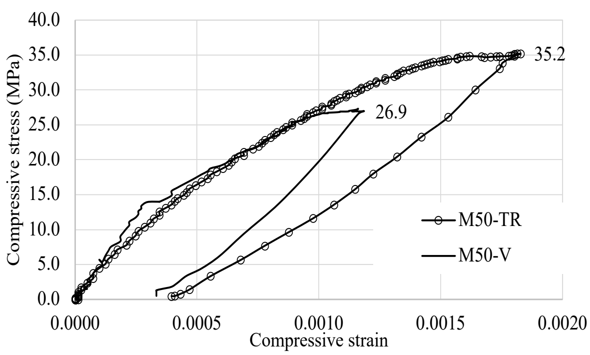
	Ratio of the stirrup amount	Ratio of the peak compressive stress
V-3/V-1	3.50	1.16
V-2/V-3	1.60	1.26

Note: The ratio of stirrup amounts can be evaluated by the ratio of the stirrup spacings.

stirrups) reached at a value of 29.2 MPa, while that of Specimen M80-TR (with diamond stirrups) was 33.6 MPa, 15% greater than the former value. The difference in terms of the peak axial stress for a spacing of 50 (mm) is even more impressive, that is as high as 30%, as can be observed in Fig. 7(b). It is worth-noting that, although all specimens were loaded with load-controlled procedure, the specimens having diamond stirrups was more ductile as their strain values corresponding to the peak stresses were significantly greater than those of the specimens having not such closed stirrups. This also addressed the effectiveness of the diamond stirrups in enhancing the structural ductility of RC columns.



(a) Specimens with a stirrup spacing of 80 mm (Group 3)



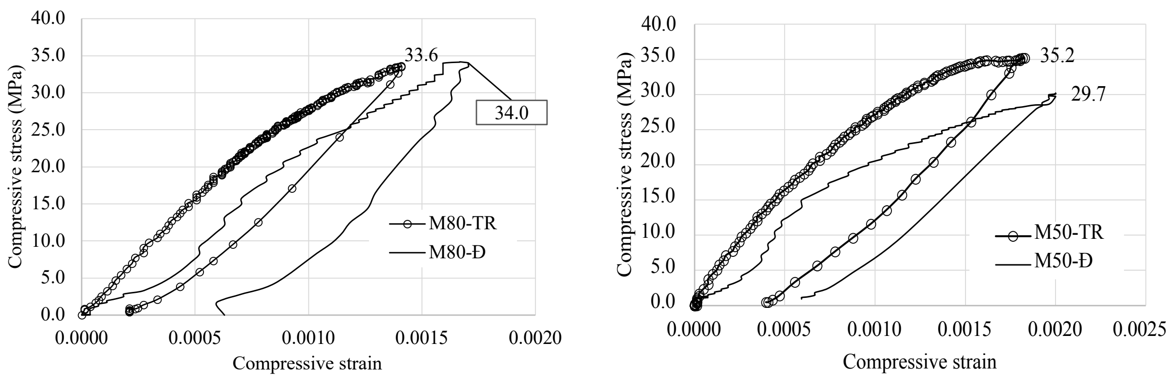
(b) Specimens with a stirrup spacing of 50 mm (Group 2)

Figure 7. Stress-strain curves of Specimens w/o diamond-shaped stirrups

3.3. Effectiveness of diamond stirrups and cross ties

It has been traditionally believed that diamond stirrups can be a better choice over the cross links in terms of enhancing structural performance of vertical elements such as RC columns and walls since the former type is closed, while the latter is not. In some current design guidelines for high-rise building structures, it is compulsory to reinforced all primary columns with these closed stirrups, especially for those at the ground and basement floors.

However, for low-rise building columns, it is not convenient and very time-consuming to fabricate their reinforcement cages with the diamond stirrups. Meanwhile, the detailing process with cross links is preferable for it can be done faster and independently from other processes. Given the contradictions in terms of traditional application and easiness of detailing procedure at site, Figs. 8(a) and 8(b) compares the stress-strain curves of Specimens M80-TR and M50-TR that were reinforced with diamond stirrups, and two Specimens M80-Đ and M50-Đ that were reinforced with cross links.



(a) Specimens with a stirrup spacing of 80 mm (Group 3) (b) Specimens with a stirrup spacing of 50 mm (Group 2)

Figure 8. Stress-strain curves of Specimens with diamond-shaped stirrups and cross-links

As can be seen in these Figures, in terms of the peak axial stress, the specimens reinforced with cross links can be either comparable (Specimen M80-Đ versus Specimen M80-TR at a spacing of 80 mm), or only slightly lower (Specimen M50-Đ versus Specimen M50-TR at a spacing of 50 mm) than those reinforced with diamond stirrups. Furthermore, the use of cross links seems to be more effective in enhancing structural ductility as the strain values corresponding to the peak axial stress of two specimens M80-Đ and M50-Đ are considerably greater than those of specimens M80-TR and M50-TR. It seems that cross links are more suitable to reinforce the low-rise building columns than diamond-shaped stirrups.

4. Conclusions

This paper presents an experimental programme on the effectiveness of stirrups on improving the axial load-resistance of RC low-rise building columns. Three batches consisting of 9 column specimens that were detailed with different stirrup types have been statically tested to failure under concentrically axial load procedure. The test performances including the specimen's failure modes and the axial stress-strain relationships were consistent throughout all specimens, showing the reliability of the test setup and the testing method.

The current test data have shown that providing an increasing number of stirrups can generally help to improve the structural performance of columns in low-rise building structures. The stirrups can be either the outer wrapping around all longitudinal bars or that combined with cross ties and the diamond shaped. A close spacing less than 100 mm can be recommended for columns subjected to high axial compression load, especially for the column end sections where the internal stresses are most complicated.

Whenever the use of inner stirrups is necessary, providing cross ties, instead of diamond links, is recommended for the columns due to the easiness of the fabricating process for such inner stirrups while the enhancing effects on the load capacity of columns can be kept the same.

Due to limited funding, there have been only 9 column specimens tested in this experimental programme. Further investigation, both experimental and theoretical, are therefore needed in order to quantify the enhancement of stirrup detailing.

Acknowledgements

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