Does the degree of tensile strain have an impact on the cracking behavior of vertical structural elements?

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Abstract. Given the random nature of crack formation, research into reinforced concrete members in the context of cracking behavior proves difficult. Therefore, widely accepted methodologies for predicting crack characteristics, e.g. crack width and spacing and number of cracks, have not been developed yet. Furthermore, cracking for members strained to high degrees of elongation, as happens during earthquakes, has not been investigated before. This experimental work aims to look into the impact, primarily of tensile deformation’s mechanical factor, in terms of cracking behaviour. Four test specimens were strained under uniaxial tensile loading. The degrees of elongation used were equal to 10‰, 20‰, 30‰ and 50‰. Useful conclusions concerning cracking behaviour are derived.

1. Introduction

Several international researchers have explored the phenomenon of cracking in reinforced concrete structures [1]–[23]. Although most of the given structures are typically reinforced in two directions, most studies carried out worldwide to investigate the behaviour of cracking have involved uniaxially tensiled reinforced concrete members with reinforcement in only one direction. To date there is not yet a widely established and accepted methodology for predicting cracking characteristics, e.g. crack widths and spacings between cracks [7], [9], [10], [23]–[26]. In addition, most of the existing research conducted has been strictly limited to the state of the stabilized crack pattern only and does not involve cracking behaviour and crack characteristics deep in the yield region [27], [28].

In the framework of the current study, an experimental program has been conducted involving reinforced concrete members detailed in two directions using longitudinal rebars and transverse reinforcement in the form of ties. This is a common construction practice used in the vast majority of concrete structures. As per the results outlined within this work, cracking behaviour and the crack characteristics are discussed. Useful conclusions concerning cracking under different degrees of elongation are derived. The experimental procedure of the current study has taken place in Aristotle University of Thessaloniki at the Laboratory of Strength of Materials but the result analysis has taken place in Democritus University of Thrace.

2. Experimental program

2.1. Detailing of test specimens

The current experimental program consists of four test specimens. The thickness of each specimen is 7.5 cm and the length of the cross-section is 15 cm. The ratio between the length and the thickness of the cross-sectional area is equal to 2, which is a typical ratio for constructing reinforced concrete
columns. The total height of the test specimen is equal to 90 cm. Each of the four specimens is subjected to a uniaxial central tensile loading. The main test element is between the metal plates and its height is 64 cm (Fig. 1).

Table 1 shows the geometrical and detailing characteristics of all four specimens. All four segments tested here have been detailed in two directions through deformed bars in terms of reinforcement. The reinforcement of each specimen simulates a typical reinforcement found in the reinforced concrete columns of typical construction buildings or in the confined boundaries of reinforced concrete seismic walls. The construction scale used to simulate typical columns or typical confined boundaries was equal to 1:3, which is commonly used for research purposes worldwide [29], [30].

The number of longitudinal bars is equal to six. Four of them have a diameter of 8 mm and two of them have a diameter of 10 mm. The longitudinal reinforcement ratio is equal to 3.19%. The transverse reinforcement consists of transverse ties placed along the height of the prism. The centre-to-centre distance between two ties is about 3.3 cm and the diameter of each tie is 4.2 mm. The only variable differentiating specimens from each other is the tensile strain. The nominal tensile strain takes values equal to 10.00%, 20.00%, 30.00% and 50.00%. It is well known that in real constructions, tensile strains up to 30.00% have been observed [31], [32]. Also, modern seismic and concrete codes
have related provisions allowing large tensile strains for reinforcement bars [33]–[39]. The name of each specimen is of the type H-“Number”, where “H” corresponds to the high longitudinal reinforcement ratio of the elements and the number shows the degree of elongation applied to the specimen in question.

### Table 1. Geometrical and detailed properties of element specimens.

| N/A | Specimen name | Length (cm) | Thickness (cm) | Effective height (cm) | Longitudinal reinforcement | Longitudinal reinforcement ratio [ρl] (%) | Transverse reinforcement | Nominal tensile strain (%) |
|-----|---------------|-------------|----------------|-----------------------|---------------------------|------------------------------------------|-------------------------|---------------------------|
| 1   | H-10         | 15          | 7.5            | 64                    | 4xD8 + 2xD10              | 3.19                                     | D4.2@33 mm              | 10.00                     |
| 2   | H-20         | 15          | 7.5            | 64                    | 4xD8 + 2xD10              | 3.19                                     | D4.2@33 mm              | 20.00                     |
| 3   | H-30         | 15          | 7.5            | 64                    | 4xD8 + 2xD10              | 3.19                                     | D4.2@33 mm              | 30.00                     |
| 4   | H-50         | 15          | 7.5            | 64                    | 4xD8 + 2xD10              | 3.19                                     | D4.2@33 mm              | 50.00                     |

2.2. **Test setup for loading**

A universal testing machine was used to apply the load. For example, for specimen H-20, the nominal degree of elongation is 20.00‰. Fig. 2 displays the experimental configuration for imposing the tensile load. The rate of loading was slow, of the order of 4 mm/min, so no result was affected by the influence of the strain rate. This is well established in international bibliography and it is a common practice [40].

![Figure 2. Loading test configuration.](image)

3. **Discussion of results**

3.1. **Experimental findings**

Fig. 3 presents the change of tensile strain relative to the tensile load imposed on the test elements. It is obvious that specimens with a high nominal degree of elongation are subjected to high tensile strains too and vice versa. It is noted that the nominal degrees of tensile strain (10‰, 20‰, 30‰, 50‰)
are slightly different from the residual actual tensile degrees, but these differences are small and negligible.

After conducting the experiments, different cracking formations and eventually cracking characteristics were noticed for each specimen. Fig. 4 shows the state of each specimen after the end of the uniaxial tensile test. Cracks of small width are obvious for specimens with low degrees of tensile strain (10‰ and 20‰), while cracks of moderate and large width are present for specimens strained under larger degrees of elongation (30‰ and 50‰). It is apparent that the final cracking formation differs between the specimens, depending on the tensile strain they have sustained.

![Figure 3](image3.png)

**Figure 3.** Diagram of tensile load versus elongation.

![Images](image4.png)

(a) H-10, (b) H-20, (c) H-30, (d) H-50

**Figure 4.** Specimens after the uniaxial tensile test: (a) H-10, (b) H-20, (c) H-30, (d) H-50.
3.2. Analysis of experimental findings

The results of the analysis of the test findings for all segments are brought together in the following tables and diagrams. Table 2 and Table 3 present the width and spacing characteristics of the cracks. Fig. 5 displays the variation of the crack width and spacing characteristics. Fig. 7 – Fig. 13 use bar charts to display the results for the same type of cracking characteristics, e.g. minimum width, average spacing, etc.

**Table 2.** Crack width characteristics.

| N/A | Specimen | Number of cracks [N] | Minimum crack width $[W_{\text{min}}]$ (mm) | Maximum crack width $[W_{\text{max}}]$ (mm) | Average crack width $[W_{\text{ave}}]$ (mm) | $W_{\text{min}}/W_{\text{ave}}$ | $W_{\text{max}}/W_{\text{ave}}$ | $W_{\text{max}}/W_{\text{min}}$ |
|-----|----------|----------------------|---------------------------------------------|---------------------------------------------|---------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1   | H-10     | 11                   | 0.2                                         | 1.0                                         | 0.655                                 | 0.31                          | 1.53                          | 5.00                          |
| 2   | H-20     | 12                   | 0.2                                         | 1.5                                         | 1.050                                 | 0.19                          | 1.43                          | 7.50                          |
| 3   | H-30     | 13                   | 0.6                                         | 2.0                                         | 1.354                                 | 0.44                          | 1.48                          | 3.33                          |
| 4   | H-50     | 13                   | 0.8                                         | 3.2                                         | 2.277                                 | 0.35                          | 1.41                          | 4.00                          |

**Table 3.** Crack spacing characteristics.

| N/A | Specimen | Number of cracks [N] | Minimum crack spacing $[S_{\text{min}}]$ (cm) | Maximum crack spacing $[S_{\text{max}}]$ (cm) | Average crack spacing $[S_{\text{ave}}]$ (cm) | $S_{\text{min}}/S_{\text{ave}}$ | $S_{\text{max}}/S_{\text{ave}}$ | $S_{\text{max}}/S_{\text{min}}$ |
|-----|----------|----------------------|---------------------------------------------|---------------------------------------------|---------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1   | H-10     | 11                   | 4.3                                         | 10.4                                        | 6.540                                 | 0.66                          | 1.59                          | 2.42                          |
| 2   | H-20     | 12                   | 2.6                                         | 10.6                                        | 5.855                                 | 0.44                          | 1.81                          | 4.08                          |
| 3   | H-30     | 13                   | 2.6                                         | 7.6                                         | 5.533                                 | 0.47                          | 1.37                          | 2.92                          |
| 4   | H-50     | 13                   | 2.9                                         | 9.0                                         | 5.575                                 | 0.52                          | 1.61                          | 3.10                          |

**Figure 5.** Change of crack width relative to the degree of elongation.
Figure 6. Change of crack spacing relative to the degree of elongation.

Figure 7. Bar chart of number of cracks regarding the degree of elongation.
**Figure 8.** Bar chart of minimum crack width as a percentage of the minimum crack width of the reference specimen.

**Figure 9.** Bar chart of maximum crack width as a percentage of the maximum crack width of the reference.
**Figure 10.** Bar chart of average crack width as a percentage of the average crack width of the reference specimen.

**Figure 11.** Bar chart of minimum crack spacing as a percentage of the minimum crack spacing of the reference specimen.
Figure 12. Bar chart of maximum crack spacing as a percentage of the maximum crack spacing of the reference specimen.

Figure 13. Bar chart of average crack spacing as a percentage of the average crack spacing of the reference specimen.
The experimental findings of the test elements were then analysed and evaluated:

1. The number of cracks appearing increases by one crack for each elongation degree, 10‰, 20‰, 30‰, and remains constant thereafter for the elongation degree of 50‰. For a better understanding of this phenomenon, more experiments concerning different longitudinal reinforcement ratios and arrangements of rebars need to be performed.

2. Comparing the crack width with the degree of elongation applied, it can be seen that the width becomes larger as the elongation degree sustained increases (Table 2, Fig. 5). It is noteworthy that all types of crack width increase with the increment of the tensile degree – meaning the minimum, maximum and average crack width.

3. It seems that there is a general trend for decreased crack spacing compared to the spacing of cracks for the initial degree of elongation of 10‰ (Fig. 6). The explanation for this may be that the number of cracks formed increases for degrees higher than the initial 10‰, which eventually translates to smaller spacings between a larger number of cracks.

4. The spacings remain almost constant between cracks, independent of the degree of elongation.

5. The damage state of specimens indicates that cracks appear at or near to the tie positions (Fig. 4). Thus, the presence of steel ties helps and promotes the disorganization of concrete around them.

4. Conclusions

This paper looks at four specimens to investigate cracking formation and behaviour in terms of the number of cracks, their width and spacing. The following conclusions are drawn:

1. The degree of tensile deformation holds a significant part in terms of the formation of cracks and their characteristics, e.g. the number of cracks formed, the width and spacing of cracks – whether considering the minimum, maximum or average value.

2. Higher degrees of elongation result in cracks with larger widths. Thus, the design of reinforced concrete structural components should take into account the degree of elongation because, as it is well known, large crack widths can lead to oxidation and deterioration of rebars and eventually affect structural safety.

3. The spacing between cracks seems to be affected when a higher tensile degree leads to a higher number of cracks. Otherwise, spacing characteristics remain more or less unaffected too.

4. The question arises of whether the longitudinal ratio or whether the arrangement of rebars plays an essential role, too. Further research is needed on the subject using test specimens with different longitudinal reinforcement ratios and arrangements. This will help to check the impact that the mechanical factor of reinforcement ratio has.

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