Analytical study on the effect of extreme seismic strains on the transverse buckling of ultra-reinforced seismic walls and their environmental design

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Abstract. In the context of the present work, the influence of the degree of tension on the phenomenon of transverse instability of reinforced concrete seismic walls is examined. Useful conclusions are drawn regarding the influence of the degree of elongation on the phenomenon of transverse buckling. These conclusions are substantiated both experimentally and analytically, as the results of the experiments are compared with the corresponding results of the analytical investigation. Moreover, some thoughts on a more environmental design of R/C seismic walls are stated. The present investigation is both experimental and analytical and consists of 4 test specimens. These specimens simulate the extreme boundary edges of structural walls. All columns simulate only the extreme reinforced areas of the walls, in order to study the basic mechanism of the phenomenon. The detailing of the specimens consists of 6 rebars with a diameter of 12 mm for each bar. The geometric dimensions are the same for all specimens. What differentiates the specimens from each other is the degree of tension they have sustained. More specifically, the tensile degrees used are 10‰, 20‰, 30‰ and 50‰. The loading stages of each specimen for all specimens are as follows: (a) Uniaxial central tensile loading on each test specimen apart from the specimen sustained 0‰ degree of tension; (b) Uniaxial central compression loading on each specimen till its failure due to buckling or due to an excess of its cross-section compressive strength. The present study focuses on the tensile loading stage only. Extreme tensile strengths are also used, e.g., 30‰ and 50‰, in order to take into account, the cases of extreme seismic excitations. The experimental study is followed by the numerical investigation of these 4 specimens using appropriate statistical software and finite elements.

1. Introduction

One crucial type of failure of reinforced concrete seismic walls is the lateral buckling [1,2]. In international bibliography, it can be found either as lateral buckling or transverse buckling or out-of-plane buckling. The terminology instability is used sometimes, too instead of buckling. Several researchers worldwide have investigated this particular phenomenon and the mechanical parameters influencing it [3–21]. The basic parameters examined were degree of elongation, longitudinal reinforcement ratio and slenderness [22–28] and reference to the cost and the resulting environmental impact is done, too [29–31].

The present study uses experimental tests performed in the past by the first author trying to investigate the mechanical parameters affecting the transverse instability [4]. These specimens were subjected to low, medium and high tensile strains equal to 10‰, 20‰, 30‰ and 50‰. In the framework of the present work, the four specimens subjected to tensile loading are modelled using finite element analysis and the results of this analytical investigation are compared to the existing experimental results concerning the tensile loading stage. It is noted that the experiments have taken
place at the Laboratory of Strength of Materials of the Aristotle University of Thessaloniki and the analysis of the results has taken place at the Democritus University of Thrace.

2. Experimental research

2.1. Test specimen characteristics

The experimental investigation for the four test specimens has been described in detail by the first author in the past [4]. Figure 1a shows the geometrical characteristics of the four test specimens, while Figure 1b displays the load test setup used for the application of the tensile loading. It is noted that the tensile loading is the first stage of the two loading stages. In the framework of the present study, only the experimental results of the tensile loading stage are compared to the analytical ones. Table 1 shows the test specimens’ characteristics.

| N/A | Specimen | Dimensions (cm) | Longitudinal reinforcement | Transverse reinforcement | Longitudinal reinforcement ratio (%) | Elongation Degree (%) |
|-----|----------|-----------------|-----------------------------|--------------------------|------------------------------------|----------------------|
| 1   | UR-10    | 15x7.5x76       | 6xD12                       | D4.2@33 mm               | 6.03                               | 10.00                |
| 2   | UR-20    | 15x7.5x76       | 6xD12                       | D4.2@33 mm               | 6.03                               | 20.00                |
| 3   | UR-30    | 15x7.5x76       | 6xD12                       | D4.2@33 mm               | 6.03                               | 30.00                |
| 4   | UR-50    | 15x7.5x76       | 6xD12                       | D4.2@33 mm               | 6.03                               | 50.00                |

Figure 1. (a) Vertical reinforcement layout, (b) Test setup for tensile loading.

2.2. Materials

For all test specimens, materials used for their construction and their characteristics were also described in the past [4]. Table 2 displays the concrete resistance for all test specimens at 28 days and...
at the day the compression test has taken place while Table 3 shows the mechanical properties for the longitudinal steel and the transverse ties.

**Table 2. Concrete mechanical properties.**

| N/A | Specimen | Concrete cube resistance (28 days) (MPa) | Concrete cube resistance (Compression test day) (MPa) | Concrete cylinder resistance (Compression test day) (MPa) |
|-----|-----------|----------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| 1   | UR-10     | 34.96                                  | 34.52                                               | 28.23                                               |
| 2   | UR-20     | 34.96                                  | 34.52                                               | 28.23                                               |
| 3   | UR-30     | 34.96                                  | 34.52                                               | 28.23                                               |
| 4   | UR-50     | 34.96                                  | 34.52                                               | 28.23                                               |

**Table 3. Reinforcement mechanical properties.**

| Reinforcement          | Yield strength (MPa) | Ultimate strength (MPa) |
|------------------------|----------------------|-------------------------|
| D12 (Longitudinal reinforcement) | 560.27               | 666.43                  |
| D4.2 (Transverse ties)  | 674.01               | 674.01                  |

2.3. **Experimental results**

Each one of the four test specimens has been subjected to a different degree of elongation [4]. Figure 2 displays the shape of specimens after the uniaxial tensile test has taken place. It is obvious that several cracks of different width have formed as it has happened in other similar experiments [32].

![Figure 2](image_url)

**Figure 2.** Specimens after the uniaxial tensile test: (a) UR-10, (b) UR-20, (c) UR-30, (d) UR-50.

3. **Analytical research**

3.1. **Modeling of test specimens**

The analytical research has taken place using a finite element software. 3D elements were used to model all four test specimens subjected to tensile loading. It is noted, as it has been mentioned before, that the present work focuses on modelling only the first stage of loading; meaning the tensile loading path till certain preselected and different degrees of elongation. For the concrete material, the inelastic
concrete model of isotropic plasticity from the software library has been chosen. For the reinforcement bar material, the properties derived from experiments are implemented in the software in order to model the inelastic behaviour of reinforcement steel. A bilinear isotropic model has been chosen for the behaviour of rebar steel. The same inelastic model has been selected to model the behaviour of the steel used for the transverse ties. 3D finite elements having an edge of 2 cm are used for the modelling of the concrete column section. Both the longitudinal reinforcement and the transverse ties are modelled using 3D finite elements having a length equal to 1 cm. Figure 3 shows the 3D model of the column both for the whole column section and the reinforcement steel. The column model is considered fixed at its base.

![Figure 3](image)

(a) 3D model for column, (b) 3D model for the column reinforcement.

3.2. Analytical results
Figure 4 displays the displacement along the column height after the end of the tensile loading test.

![Figure 4](image)

(a) UR-10, (b) UR-20, (c) UR-30.
4. Analysis of results

4.1. Analytical versus experimental results
A comparison takes place between the load versus elongation diagrams which have resulted from the experimental tensile tests and the numerical tensile tests (Figure 5 - Figure 8).

**Figure 5.** Load versus elongation diagram for specimen C-10.

**Figure 6.** Load versus elongation diagram for specimen C-20.

**Figure 7.** Load versus elongation diagram for specimen C-30.

4.2. Analysis of results
The analysis of the previous results leads to the following:
1. Figure 4 displays the displacement along the Z-axis which coincides with the height of the prism specimens modelling the extreme edges of seismic walls. All specimens are strained till the preselected displacement according to the preselected tensile degree.

2. The vertical displacement is zero at the base of the prisms since the base is fixed (Figure 4). The maximum vertical displacement is found towards the upper part of the specimens where the tensile load is applied. The same phenomenon takes place in the tensile experiments where the tensile load is applied at the upper part of the test specimens while at the bottom part the test specimens are held rigidly by the grapples of the tensile machine.

3. It is obvious that there is a very good correlation between the experimental and the analytical results for all test specimens (Figure 5 - Figure 7). Both the elastic and the plastic branch coincide between the experiments and the analyses.

4. It is noteworthy that yielding takes place almost at the same load both for the tests and the analyses for all test specimens.

5. Only the effective length of the specimens has been modelled, since this is the length within which the tensile elongation appears (Figure 1). The effective length is equal to 640 mm (Figure 1).

5. Conclusions
In the framework of the current research, an analytical investigation has taken place including numerical analyses of four test specimens modelling the extreme ends of R/C seismic walls. The numerical analyses have taken place using 3D finite elements. The results from the numerical analyses are compared to the relevant experimental results from the same test specimens found in a previous publication of the first author. The following conclusions can be drawn:

1. There is an almost excellent correlation between the experimental results and the analytical results concerning the load-displacement diagrams of the tensile loading.

2. The elastic branch, the yielding point and the plastic branch coincide almost perfectly for all test specimens.

3. The degree of elongation is a very crucial mechanical parameter that affects tremendously the behaviour of the boundary edges of structural walls and its investigation has to be applied in the proper and right way following a correct procedure. The convergence between the experimental and the numerical results proves that the procedure applied, in the present work, follows the right path.

4. A future research could and should model the whole test specimen and not only the effective length in order to simulate even more precisely the experimental behaviour. Then this more precise analytical behaviour could be compared again with the relevant experimental results.

5. It is obvious that if lateral buckling could be halted using less materials, meaning less concrete volume and less weight of concrete bars, this would have led to a better construction cost which would have resulted to a decrease to the emissions produced when these materials are manufactured. The environmental emissions are proportional to the quantity of materials used. If large amounts of materials are used for the building’s construction, then the emissions would be large, too. On the other hand, if small amounts of materials are used, then the emissions would be small, too. It is obvious that a future research should emphasize on the fact of minimising or halting transverse instability by using less materials of concrete and reinforcement steel, so the resulting emissions would have decreased. Thus, the environmental impact would have been affected, too.

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