Inclined struts variation and its effect in reinforced concrete design

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ABSTRACT: Cracks developing in high intensive shear areas are largely dictated by the effect of variable levels of flexural moments and their direction at the supports regions. Changes in developing crack inclinations, lead to changes in developing strut inclinations available for pressure, creating a sort of truss and allowing the transfer of forces for equilibrium. Strut and tie model analysis of reinforced concrete elements is considered an alternative to the usual approaches of analysis and design, and is applied effectively in regions of discontinuity. This analysis follows the truss analogy approach. Inclined concrete compression struts between parallel inclined cracks are assumed. The variation of the struts' angle of inclination, depending on the shear and flexure levels, and its effect in reinforced concrete design are researched. This research introduces a rapid and approximated methodology for the representation of struts' angle of inclination in analytical modelling of shear computations as customary in codes of practice

KEYWORDS

Structural design, nonlinear analysis, cracking, building materials, constitutive laws, mechanical properties.

1 INTRODUCTION

The objective of concrete shear design is to identify the quantity, shape and placement of the required shear reinforcement to prevent brittle shear failure (which can occur without warning).

Shear design procedures for reinforced concrete elements are based on different mechanisms of shear transfer. Among these: fracture mechanics approaches, shear-friction hypothesis, tooth models, compression field theory, modified compression field theory and truss model approaches are the most used ones.

With the compression field theory methods, equilibrium conditions, compatibility conditions, and stress-strain relationships for both the reinforcement and the diagonally cracked concrete are used to predict the load-deformation response of a section subjected to shear. On the other hand, for the truss model methods, compressive struts represent the flow of concentrated compressive stresses in the concrete and tension ties represent the reinforcing steel. The diagonally stressed concrete angle (shear crack inclination) should be assumed. Different angles of diagonally compressed concrete struts lead to a different amount of reinforcement in a nonlinear solution. Larger deviations in assuming proper angle of inclination lead to higher ductility requirements.

Progressive cracking in the support regions of reinforced concrete beams as a result of shear or shear combined with flexure, in external or intermediate supports respectively, leads to changes in the load transfer mechanism to the supports. Alternatively, for large deviation from elastic behaviour, the truss analogy approach seems adequately representative in regions of high shear. Longitudinal steel serves as the tension chord of the truss, as a tie. Inclined concrete compression struts between parallel inclined cracks serve as diagonal struts.

Strut and tie modelling has been introduced in important codes: European Standard EN 1992-1-1:2004 [EC2, 2004], ACI 318-08 [ACI 318, 2008]. In the Israeli code 466 [IS 466/1, 2003] it is going to be introduced. The importance of this is emphasised by the authors.

This paper intends to introduce a study to examine continuity, fixity range, and flexural moments at support zones, affecting the diagonal strut inclination in the truss model developed to carry shear forces.

In the selection of the inclination of the path of forces, which represent the compressive struts to the supports (compression flow) a wide range of alternatives is available. Differences in assumed angles substantially affect the amount of required shear reinforcement in the design of reinforced concrete beams.

Consequently, setting longitudinal reinforcement and shear reinforcement amounts affects the way and inclination of the developing cracks. These were kept constant in this study, to isolate the effects and focus on the investigated parameters.

This study aims to lead to design assumptions guidelines, according to this approach, relative to the variation of the struts' angle of inclination.

Suitability of obtained results to available instructions (or lack of instructions) in notable codes of practice, such as EC2 (2004), ACI 318-08 (2008) and other codes will be examined.

2 COMPUTER PROGRAM AND MATERIAL MODELS

For the purpose of determining stresses and strains in concrete and tension steel in this research, a computer program for non-linear structural analysis of elements [ADINA, 2009] was used.

Figure 1 shows the non-linear stress-strain relation used in the concrete model in ADINA [ADINA, 2009] (compressive strain shown negative).

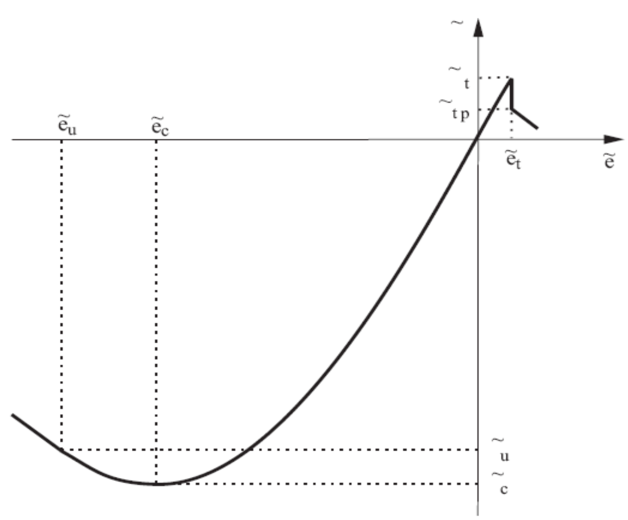

Figure 1. Uniaxial stress-strain relation used in concrete model. [ADINA, 2009]

For tension, the stress-strain relation is linear until tensile failure stress. Tensile strength in the principal direction depends on compressive stresses in the other directions.

The post failure material behaviours considered in the concrete model in ADINA [ADINA, 2009] include the post tensile cracking, post compression crushing, and strain-softening behaviours.

The adopted reinforcing steel stress-strain relation is bilinear.

3 CONSTITUTIVE RELATIONS AND CHARACTERISTICS OF MATERIALS

The model provided in ADINA [ADINA, 2009] does not contain all the desirable detailed characteristics of the concrete. However, according to the variability of concrete stress-strain relation that is described in this study, mainly by confinement contribution, suitable treatment on this subject is not in the computer program.

Ultimate compressive strain, increased characteristic strength and corresponding strain, for computer program, was computed with the contribution of confinement according to Euro code 2 [EC2, 2004] model, (Figure 2).

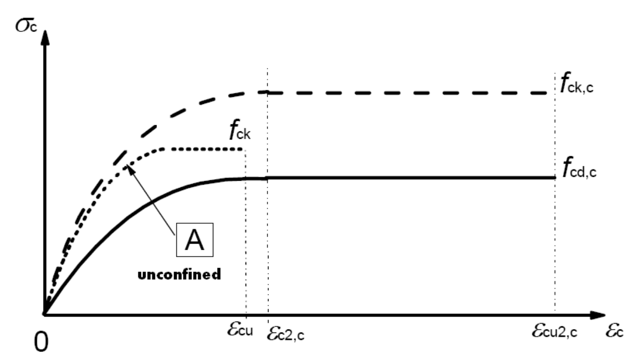

Figure 2. Stress-strain relationship for confined concrete Euro code 2 [EC2, 2004]

Characteristic tensile strength values, in the principal direction, for the variety of elements, was computed according to Euro code 2 [EC2, 2004] model, taking into account the depth of the cross section.

The characteristic values for the reinforcing steel constitutive law were determined in accordance with the accepted values in the Codes of Practice.

Characteristic yield stress was 400 MPa for ribbed bars and 240 MPa for plain bars for stirrups only.

Relatively high ductility values for the reinforcement are required by Israeli codes of design. Therefore class C of reinforcement suitable for use with Euro code 2 was selected, with characteristic strain at maximum force, at least 7.5%, compared with 12% required by Israeli codes. And for the ratio of tensile strength to the yield stress, minimum value in the range 1.15 – 1.35, compared with 1.25 considering Israeli codes.

4 DETAILED DESCRIPTION OF THE PROPOSED RESEARCH

Proposed research is theoretical at this stage. Examination of the behavior of reinforced concrete beams was studied at the advanced stages of loading, near their ultimate state. Special attention has been invested in monitoring the development of cracks as a result of shear and flexure, which serve as an indication for development of strut and tie model of behaviour, and examining the compressive struts inclination angle in the developed truss model.

Crack opening occurs, when the tensile stress in the principal stress direction exceeds the tensile strength, in a plane perpendicular to the corresponding principal stress direction. Sequence of cracks formation, in regions of high shear, indicates the angle of inclination of cracks and as an outcome, the angle of inclination of the struts.

It was aimed to examine mainly the external support regions, and the intermediate support regions, with continuity to other spans; and to concentrate on the effect of negative flexural moment in Figure 3 on the inclination of the compressive struts compared with, external pinned supports.

The main results were achieved by:

Using computer program ADINA for non-linear analysis of structural elements.

Using finite elements for representing beam element.

Using truss model to represent reinforcement bars.

Using confined concrete constitutive law, as explained earlier and detailed below.

The contribution of the confinement provided to the concrete, by transverse and longitudinal reinforcement was determined according to the procedure adopted in Euro code 2 [EC2, 2004] and Israeli code 466 [IS 466/1, 2003], see Figure 2, and expressed through the characteristic values for the confined concrete constitutive law.

Many tests were carried out to examine the mechanisms by which cracked reinforced concrete beams transmitted shear. Among the various effects which were examined: concrete strength, stress and strain in the longitudinal reinforcement, load pattern, size effect, member depth, maximum aggregate size. Different crack patterns can be seen from published experimental results. It is difficult to draw conclusions from differences between the external support regions, and the intermediate support regions, the effect which this research interest is to concentrate and mainly examine, from these published experimental results.

5 METHODOLOGY

For monitoring the influence of the continuity, on the crack development, and the angle of inclination of the compressive struts, two equal spans continuous beams supported on three supports, and one span beams supported on two supports, were selected.
Loading along beams was restricted to uniform loads at this stage of research.
Figure 3 indicates the effect of negative flexural moment at support, on the interval of variability of moments and shear forces along the beam.

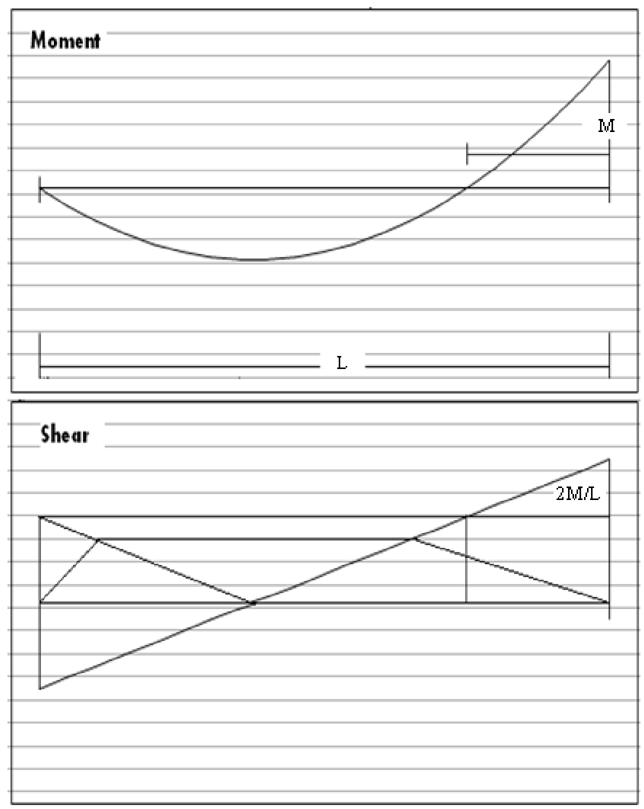

Figure 3. Moments and shear forces along a beam with continuity

Bottom shear part of Figure 3 is reflected by mirror image drawn to the upper part of the diagram.

The difference between shear forces at intermediate support relative to external support as a result of negative flexural moment at intermediate support is 2M/L.

The other lines describe the variation of the inclination angle of diagonal concrete compressive struts (in accordance with compression flow) of intermediate support region compared with external pinned support region, as assumed for examination in this research.

Applications

Several examples of beams with wide range of different sections were examined.

Span was determined to be 3.0 m, taking into consideration:

Refinement of the model to large number of finite elements, leading to more representative results, in the range of computer program limits.

Appropriate dimensions to be used for the experimental research which is due to complete this theoretical work.

Good practice of structural design is based on the principle of increasing structural redundancy. High static indeterminacy of continuous concrete beams is favourable. Preferred design process of reinforced concrete beams is that for the plastic hinge formation sequence at the ultimate limit state, the first hinges will be created over supports. Selection of longitudinal reinforcing bars, for the examples presented in this paper, and detailing along beam spans, are in correlation with accepted range of practice. On the other hand, not less important, matching desirable behaviour of continuous beams, with limited degree of redistribution, and with directing to, first plastic hinge formation, in negative moment range, over interior support. Where will be indicated, the first yielding of the top reinforcement bars.

Transverse reinforcement along the beam span for the examples presented in this paper is of the same type used for longitudinal reinforcement.

Representative results are visualized in Figure 4 – Figure11.

Figures 4 and 5 visualize the stresses which develop in the concrete. The colours indicate the stress values in the longitudinal direction. The value of the stresses along the main direction, (due to compression), are indicated by the vectors in the figures. These stresses develop before collapse at the distributed load of 4.1 t/m^2.

Figures 10 and 11 indicate the stresses which developed in the rebars due to a distributed loading of 4.1 t/m2 acting on the beams. The bar under tension represents the tie of the truss model. The stresses which develop in the rebars have maximal values which varied between 240 to 360 MPa.

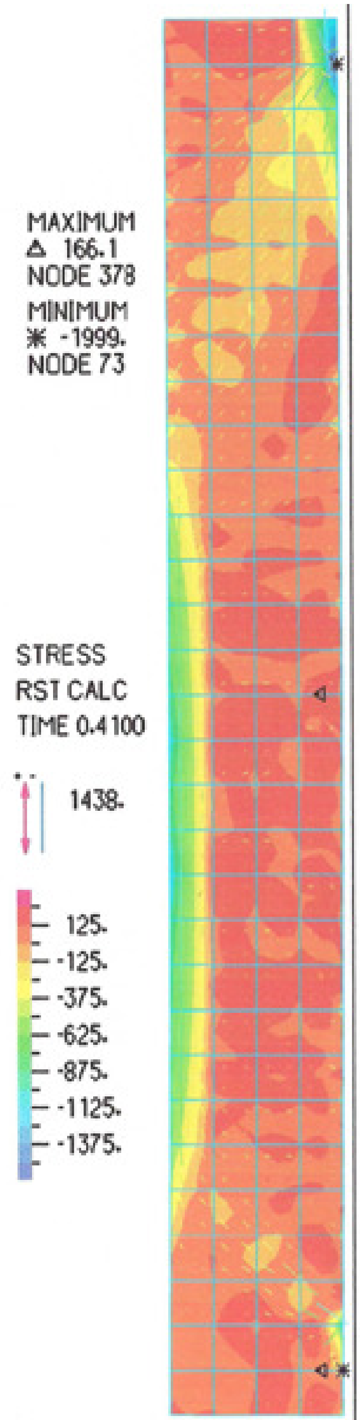

Figure 4. Results along a beam with continuity (Stresses)

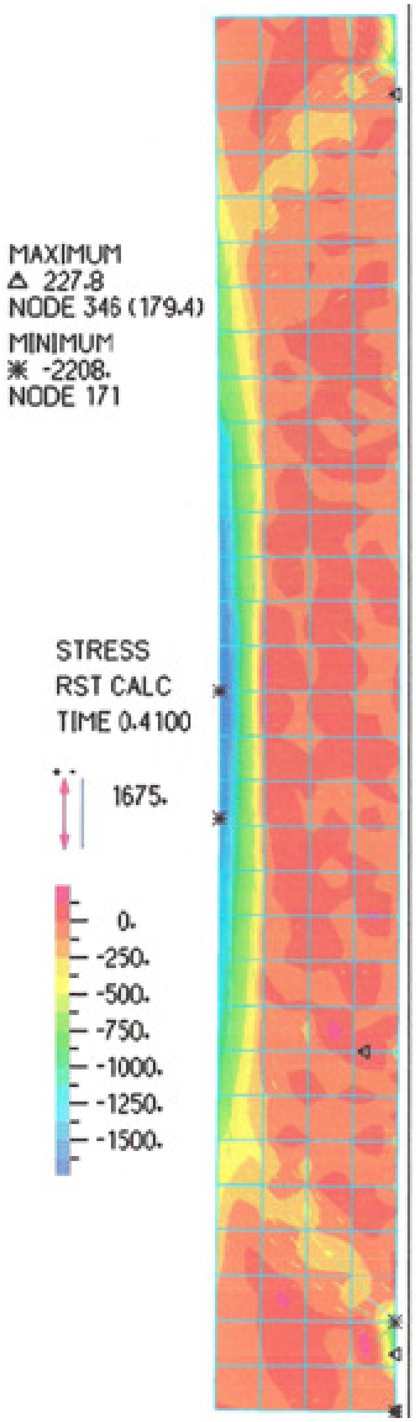

Figure 5. Results along one span beam (Stresses)

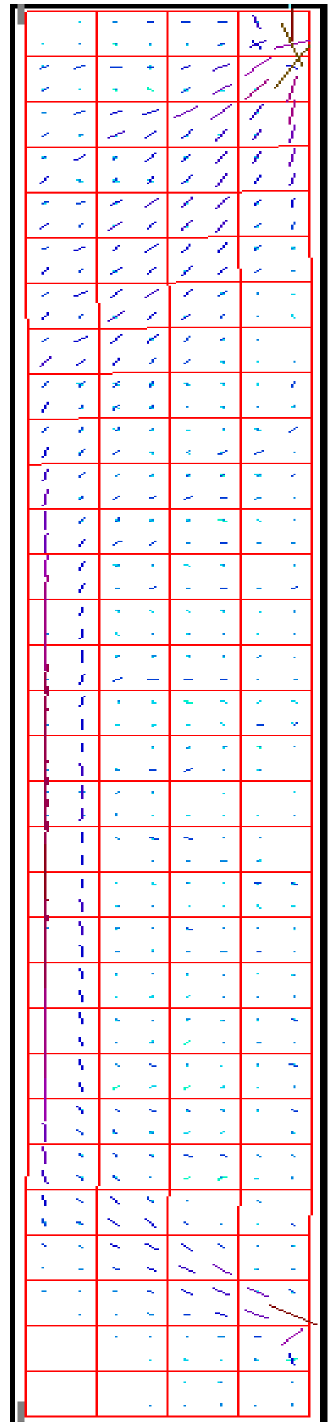

Figure 6. Results along a beam with continuity (Compression flow)

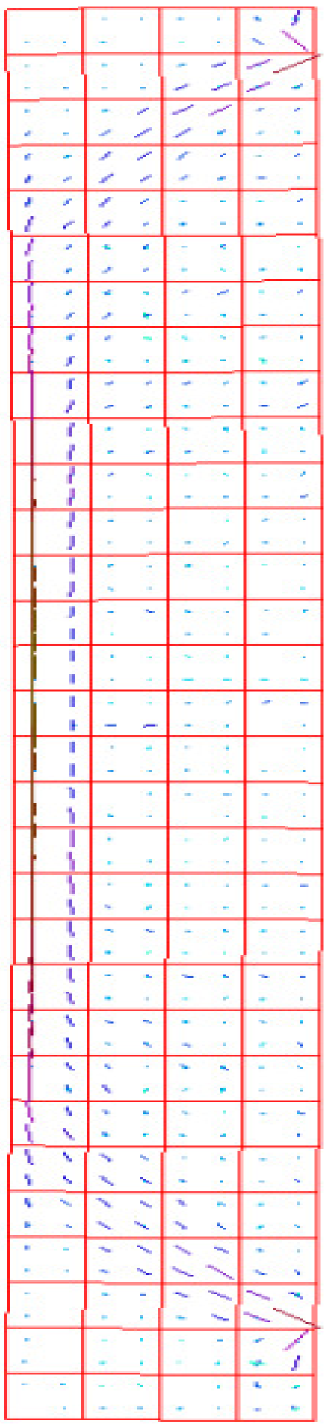

Figure 7. Results along one span beam
(Compression flow)

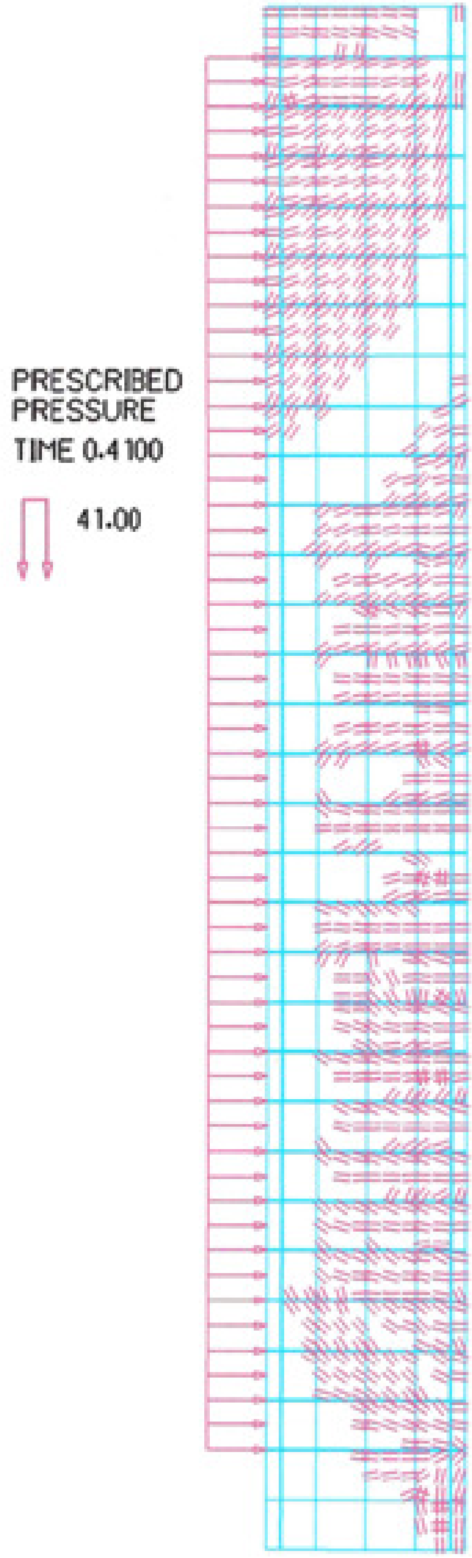

Figure 8. Results along a beam with continuity
(Crack opening)

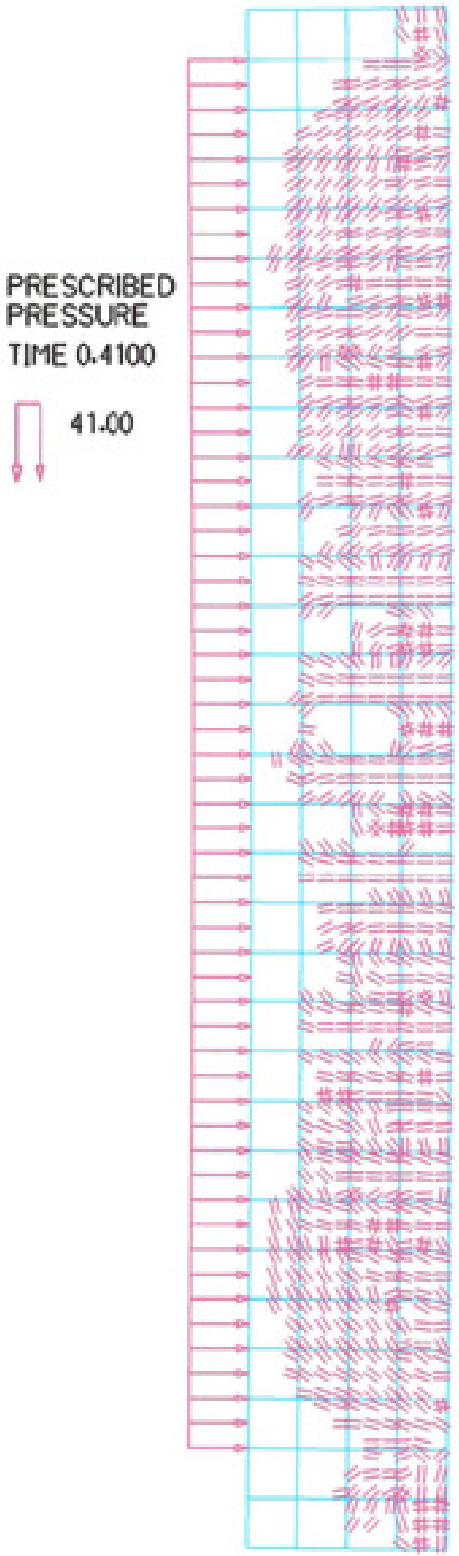

Figure 9. Results along one span beam
(Crack opening)

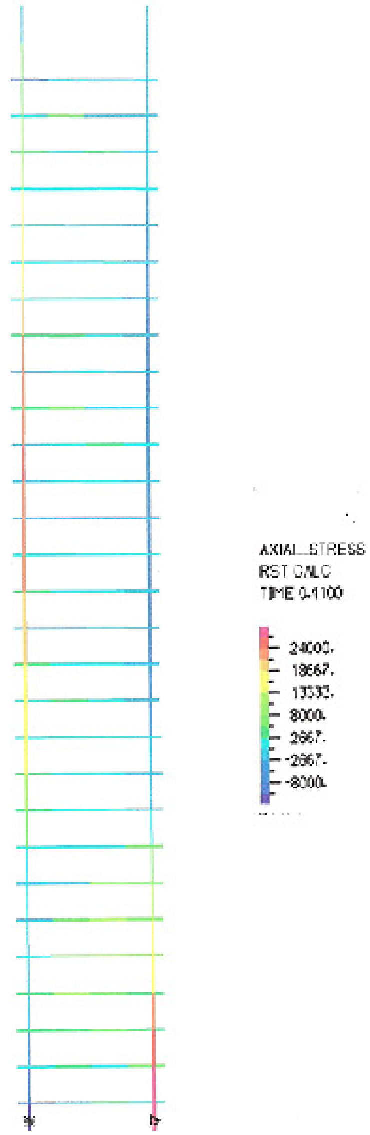

Figure 10. Stresses in the rebars of the continuous beam [t/m2]

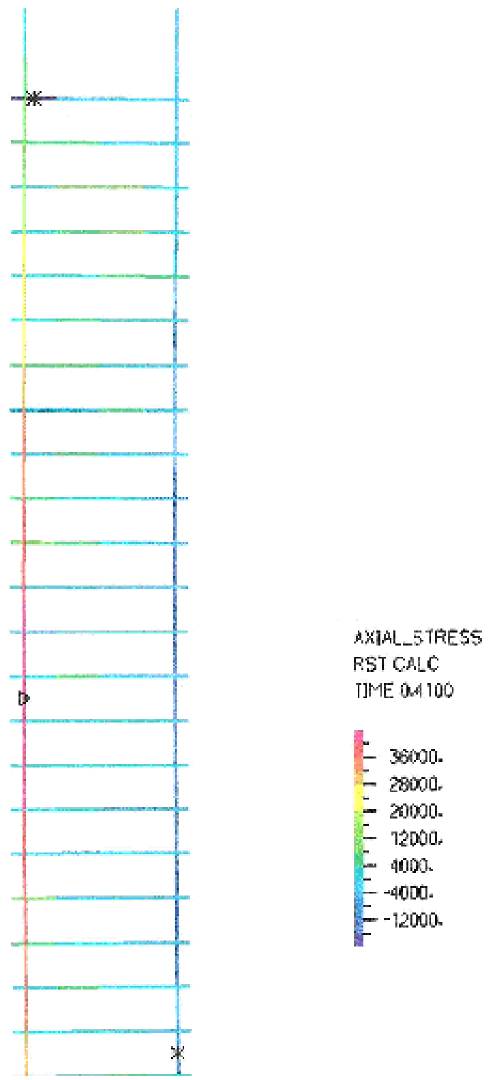

Figure 11. Stresses in the rebars of the single span beam [t/m2]

Crack development direction at the free support zone was hardly influenced by the conditions at the second support of the span with continuity and stayed in the order of 45 degrees.

However, development of cracks in internal support zones, with flexural bending moments, stretched into a broader range toward the middle of the span, even up to 50% more than the exterior support range. Those inclinations of the cracks were more moderate, with smaller angles to the beam axis; consistent with the described in Figure 3.

Quantitative determination requires experimental testing, which will be later in this research, as it is continued.

6 RESEARCH OBJECTIVES & EXPECTED SIGNIFICANCE

Shear zones at support regions of reinforced concrete beams were investigated with increasing uniform loading along beams. Nonlinear modelling and analysis were used. Monitoring the development of cracks along the beam, with progression toward ultimate limit state, indicated the directions and the variation in the potential flow directions of beam pressure.

This model of analysis in the codes is new and brief. Lack of guidance for design engineers is obvious.

7 SUMMARY

One of the numerous and interrelated factors affecting crack development in reinforced concrete beams was treated in this research.

Study presented in this paper emphasizes the influence of continuity. With emphasis on the differences between the cases of negative flexural moment development with tension at the top fibers of the beam, and the free supporting cases, with positive moments, namely tension at the lower fibers of the beam.

Crack opening and development, can be helpful for codes guidelines related to struts inclination determination, in calculations conducted for the shear forces in reinforced concrete elements, in advanced stages of crack development. This approach does not cover service state design, which should be carried out separately.

For validation and strengthening the results from this study, further practical test experiments are required. Tests should isolate, focalize and emphasize the influence of the parameters that were examined in this work. This article will be followed by the next report based on experimental results.

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