NON-LINEAR FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE MEMBERS USING MSC/NASTRAN

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ABSTRACT

Non-linear finite element (FE) analysis of reinforced concrete (RC) members like beams, slabs etc. using the majority of available commercial finite element software poses many numerical difficulties. Major difficulty is faced because of strain-softening behavior of concrete once it is yielded. These commercial finite element software of FE analysis remain totally inadequate in handling strain-softening behavior of concrete. This is because these software offer only the traditional non-linear solution techniques like Newton-Raphson (N-R), modified Newton-Raphson (mN-R) methods etc. which can not handle the non-linear post-yielding analyses of members made of materials like concrete, soil, rock etc. which exhibit strain-softening behaviors after their yielding. MSC/NASTRAN, however, offers many advanced solution techniques like Crisfield's arc-length (CA) method, Riks' arc-length (RA) method, and modified Riks' arc-length (mRA) method. These methods can handle the strain softening behavior adequately.

This paper presents the uses of MSC/NASTRAN and advantages of using this software for non-linear analyses of RC members. Brief discussion on modeling procedures and discussion of results of three RC shallow beams are also presented to illustrate the degree of accuracy in results which could be achieved from non-linear post-yielding analyses of R.C. members by using MSC/NASTRAN.

INTRODUCTION

Finite element method is a powerful numerical technique for analysing structures/continua. Several commercial software are available for FE analysis. MSC/NASTRAN is the most widely used general purpose software of FE analysis. It has versatile applications in the filed of static, dynamic, heat transfer, etc. MSC/NASTRAN also offers linear and non-linear (material, geometric, and boundary conditions) analysis.

The majority of the available general purpose commercial FE software are not suitable for non-linear post-yielding analyses of concrete members because unlike steel, concrete shows strain-softening behavior once it is yielded. This means that stress strain relationship of concrete follows a downward path after its yielding. The traditional non-linear solution techniques of Newton’s family only which are generally available in most of the commercial FE software can not handle this behavior and solution process stops when the magnitude of applied load reaches the yielding point (unstable region) of stress-strain curve. The advanced non-linear solution techniques like CA, RA, and mRA can handle the strain softening behavior of concrete. MSC/NASTRAN offers all these powerful and advanced non-linear solution techniques. Moreover, the other special features like *SUBCASE* and *RESTART* which are offered by MSC/NASTRAN are also very useful in the non-linear analysis of concrete members.

MSC/NASTRAN is used for modeling, non-linear post-yielding analyses, and results processing of three different RC beams. The modeling techniques, non-linear solution strategies and the uses of special features like *SUBCASE* and *RESTART* which are available in MSC/NASTRAN, to overcome the numerical complexity associated with non-linear post yielding analyses of concrete members are discussed. Results obtained from the analyses are presented and compared with the results obtained by other researchers [1,2] either from their experimental works or from FE analyses using their own FE program written specially for the analysis of concrete members.

All the discussions in this paper are made based on MSC/NASTRAN Version 68.2.

MODELING OF RC MEMBERS

Modeling is one of the most important area for finite element analysis. Accuracy in the modeling of geometry, loads, material properties, boundary conditions, and other structural properties are of absolute necessary for close numerical idealisation of the actual member/structure. Several pre-processors of MSC/NASTRAN are available for this purpose. The pre-processor, MSC/XL, was used in the present work.

MSC/NASTRAN offers various solid and line elements which can be used to model concrete and steel respectively. The choice depends on type and geometry of the structure/member. Eight-node Hexa (solid) and two-node (line) elements are used to model concrete and steel reinforcement respectively in the present work. Concrete cover in tension was neglected to avoid the complexity in geometry modeling.

Each concentrated load is represented by equivalent line load to avoid the load concentration at and around the points of application of loads.

Non-linear stress-strain with different stress-strain behavior in tension and compression for concrete as the one shown in figure 1 and bi-linear strain hardening stress-strain relationship with similar stress-strain behavior in tension and compression for steel as shown in figure 2 are adopted.

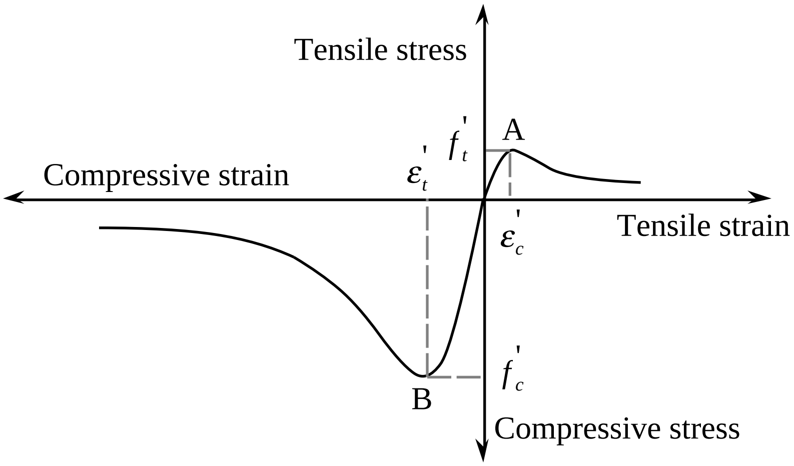

Figure 1 Typical stress-strain relationship for concrete

where A = yield point of concrete in tension

B = yield point of concrete in compression

f_c' = yield stress in concrete in uni-axial compression

f_t' = yield strain in concrete in uni-axial tension

ε_c' = compressive strain in concrete at stress f_c'

ε_t' = tensile strain in concrete at stress f_t'

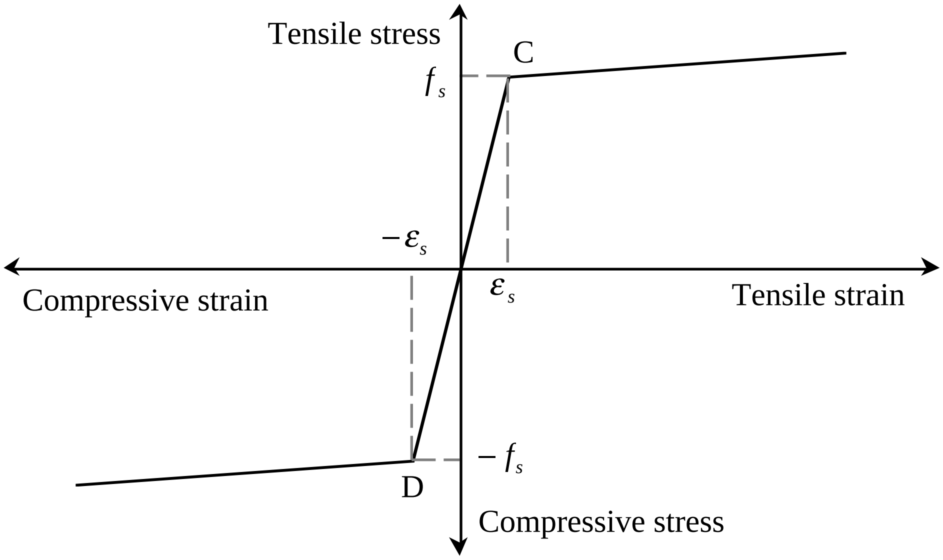

Figure 2 Typical stress-strain relationship for steel reinforcement bars

where C = yield point of steel in uni-axial tension

D = yield point of steel in uni-axial compression

f_s = yield stress of steel both in compression (negative sign) and tension (positive sign)

ε_s = strain in steel at stress f_s. Compression and tension are represented by negative and positive signs respectively.

These non-linear behavior of concrete and steel are assigned by two different *TABLES1* cards in the *Bulk Data* section. Non-linear solution is evoked by defining *SOL106* in the *Executive Control* section. Uni-axial failure criteria, both for concrete and steel as shown in figures 1 and 2 are adopted.

Boundary conditions 1,2,3 and 2,3 are defined to simulate hinge support at one end and roller support at the other end respectively.

One of the major advantages in modeling RC members in MSC/NASTRAN is that it offers Gap element. The Gap element can be made suitable to simulate cracks in the concrete. Gap element has all the properties of a crack in the concrete with some additional properties. When the gap in the Gap element is closed, it has a large axial stiffness and therefore, significant compressive and shear force may be present in this element. This behavior is similar to the behavior of crack in the concrete. It is generally assumed that the cracked concrete transfer the full compressive stress like uncracked concrete and little (reduced) shear stress only but no tensions are transferred across the closed cracks. The additional property of friction in the Gap element is assigned to be negligible/zero.

The Spring elements offered by MSC/NASTRAN are used to model the interaction between steel and concrete.

NON-LINEAR SOLUTION STRATEGIES

Non-linear solution technique and overall non-linear solution strategy to be adopted are the most important for non-linear pre- and post-yielding analyses of concrete members. The advanced non-linear solution techniques like CA, RA, and mRA are offered by MSC/NASTRAN. The stiffness matrix becomes singular at the unstable region (where stiffness matrix changes its sign from positive to negative) and becomes negative at the strain-softening region as shown in figure 3, if traditional non-linear solution techniques of Newton's family are used in non-linear analysis of concrete members. Therefore, the solution process stops without any solution. Crisfield's arc-length (CA) method is therefore, used to pass the unstable region of the stress-strain curve successfully and also in the strain softening region to avoid the numerical complexities associated with the non-linear post-yielding analyses of concrete members.

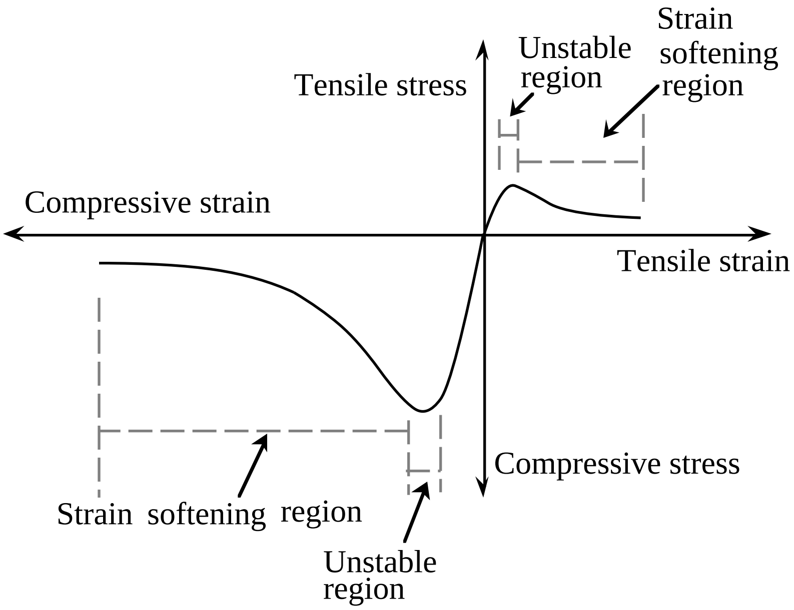

Figure 3 Unstable and strain-softening regions of stress-strain relationship of concrete

The stiffness matrix is updated either based on only load increment or only displacement increment if any non-linear solution method of Newton's family is used. Therefore, Newton's method could be trapped in an infinite loop at the unstable region. The iteration method and solution process may also stop when the stiffness matrix becomes negative if Newton's method is adopted. These difficulties could be overcome and non-positive definite stiffness matrix will be retained and used for iteration if any arc-length method is used [4]. This advantage is achieved when the arc-length method is used because both the load and displacement parameters are kept variable in arc-length method, as the constraint equation in the arc-length method is written in terms of *arc-length* ($\Delta\ell$) which is function of both of these two terms [5].

Several numerical difficulties are observed in non-linear solution process even if arc-length method is used. Load factor may become negative or regression in the solution process may occur. A suitable value of scaling factor is necessary to be defined in the *NLPCI* card for arc-length method. The adopted scaling factor defines the scaling between the load and displacement terms [5]. MSC/NASTRAN offers an option of defining suitable scaling factor by the users. Crisfield's arc-length method may become equivalent to a displacement increment method as shown in figure 4 if this scaling factor is assigned to be zero.

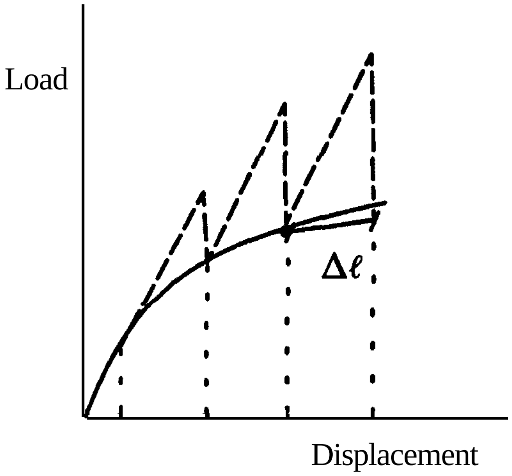

Figure 4 Crisfield's arc-length method in terms of Displacements [3]

MSC/NASTRAN also offers many other special features. *SUBCASE* is one of them. *SUBCASE* provides the options of applying the total load in different load steps and every load step with different numbers of load increment, different number of iterations for each load increment, and other controlling parameters of non-linear solution process. The *SUBCASE* is used to pass the unstable region comfortably by taking lesser applied load and higher number of load increments and iterations at this region. The other special feature *RESTART* which is used to restart the solution process from the last converged solution (which is saved by MSC/NASTRAN automatically) when the solution process stopped because of divergence or other problems. MSC/NASTRAN also offers the bisection option for each load increment. The incremental load value is bisected automatically if the convergence is not achieved in any incremental load step even after maximum number of iteration defined by the user. The allowable maximum number of bisections in each incremental load can be defined in the *NLPARM* card.

The decision about the convergence criterion to be used in the non-linear iterative solution strategy is important. Choice of convergence criterion depends on the type of structure, degree of accuracy required, efficiency in solution process required etc. MSC/NASTRAN offers various options of selecting of convergence criterion. Convergence criterion may be any combination of out-of-balance forces, change in displacements, and energy (work) error. Convergence criterion based on out-of-balance force and change in displacement is used before yielding and convergence criterion based on out-of-balance force is used after yielding because displacement is very high after yielding.

RESULTS AND DISCUSSIONS

Three different RC beams are analysed. Two of them (Beam-A and -B) are subjected to two-point concentrated loads. The Beams A and B were analysed by Kotsovos [2] using his own finite element program specially written for the analysis of concrete members. The load-vs-maximum deflection curve obtained by the authors in the current work and Kotsovos [2] are presented in figures 5 and 6. Beam-C was experimentally tested against a single-point concentrated load at the center by Johansson [1]. The load-vs-maximum deflection curve obtained by the authors and by Johansson [1] is presented in figure 7.

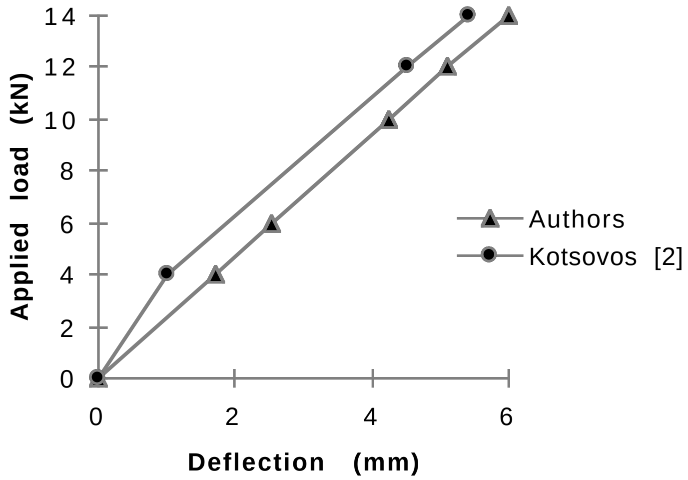

Figure 5 Load-maximum deflection relationship for Beam-A

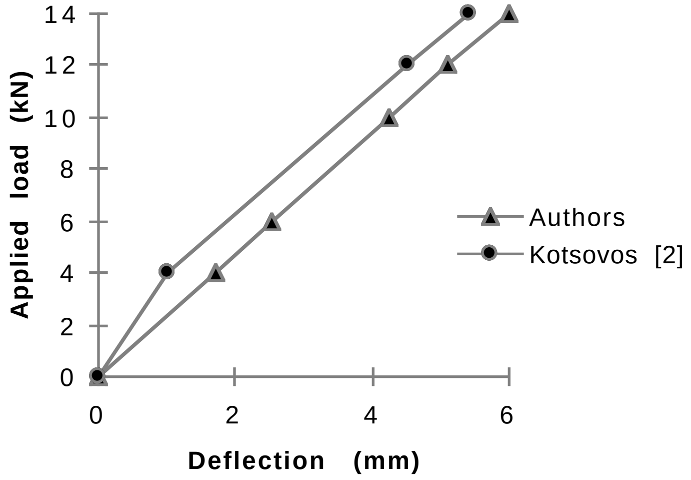

Figure 6 Load-maximum deflection relationship for Beam-B

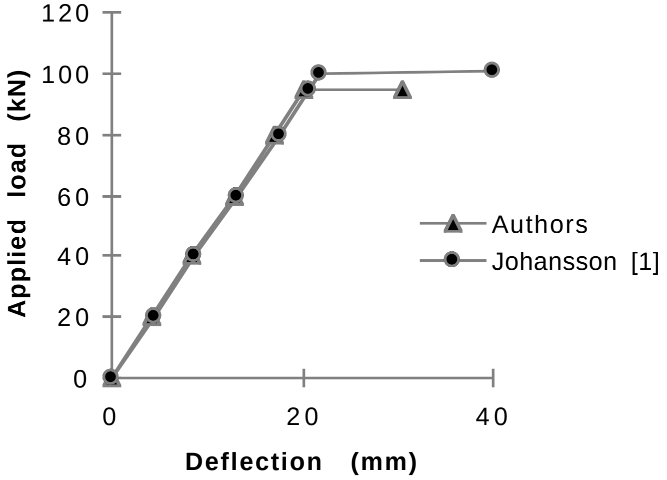

Figure 7 Load-maximum deflection relationship for Beam-C

Good agreement is achieved between the results obtained by the authors and those obtained by the other researchers [1, 2]. A little difference is observed in the case of Beam-C. This is because the finite element model is always stiffer than the real member. The negligible difference is observed in Beam-A and Beam-B. This may be mainly due to different approaches in crack modeling in concrete. The smeared (distributed) crack model was adopted by Kotsovos [2], whereas discrete crack model was used by the authors.

CONCLUSIONS

Discussion on the excellent features like the arc-length method of non-linear solution, Gap element, *SUBCASE*, *RESTART* which are offered by MSC/NASTRAN are made. The uses and advantages of using these features for modeling and non-linear FE analyses of RC members are also presented. Results obtained from the analyses of three RC shallow beams which are subjected to uni-axial stress condition, are presented and compared with the results obtained by the other researchers to illustrate the degree of accuracy in the results from MSC/NASTRAN could be obtained. A good agreement is achieved in the results obtained using MSC/NASTRAN.

It is discussed that any RC members subjected to uni-axial stress condition can be analysed using MSC/NASTRAN (Version 68.2) very successfully. MSC/NASTRAN can be used more successfully if bi-axial failure criteria of concrete, like the one proposed by Kufper *et al.* [6] is incorporated in MSC/NASTRAN. In that case MSC/NASTRAN can be used very successfully for non-linear analysis of most of the RC members.

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