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Tools for forensic analysis of concrete structures

Frank J. Vecchio†, Evan C. Bentz‡ and Michael P. Collins†

Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, Canada M5S 1A4

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Abstract. Computer-based analysis tools for forensic assessment of reinforced concrete structures are presented. The analysis tools, mostly in the form of nonlinear finite element procedures, are based on the concepts and formulations of the Modified Compression Field Theory. Relevant details regarding their formulation are provided. Development of realistic constitutive models and corroboration of the analysis procedures, through comprehensive experimental programs, are discussed. Also presented are graphics-based pre- and post-processors, which are of significant aid in structural modeling, input of data, and interpretation of analysis results. The details and results of a case study, illustrating the application and value of such analytical tools, are also discussed.

Keywords: analysis; distressed; failure; finite elements; reinforced concrete; repair; shear; structures; software.

1. Introduction

Computer-aided nonlinear analysis of reinforced concrete structures has undergone tremendous advancement since initial applications about four decades ago. Much research activity has occurred in the realm of constitutive modeling of reinforced concrete and in the development of sophisticated analysis algorithms. These advancements are well documented in various state-of-the-art reports (for example, ASCE (1982)), and are still the subject of many specialty symposia and workshops. One particularly powerful and popular approach to advanced modeling involves the use of nonlinear finite element analysis (NLFEA) techniques. The development of such procedures has progressed to the point where they are becoming practical tools for design office engineers.

Advanced analytical procedures are finding application as useful forensic analysis tools in relation to damaged or ageing structures. NLFEA procedures can be used to obtain an assessment of the safety and integrity of damaged or deteriorated structures, or structures built to superceded codes, standards, or practices deemed to be deficient today. They can be of value in assessing the behavior expected from retrofitted structures or in investigating and rationally selecting among various repair alternatives. In cases of structural failure or collapse, NLFEA procedures can be invaluable in determining the contributing factors and in suggesting remedial measures for future designs.

There remain some concerns with the use of these advanced methods, however. Accurate modeling of the complex behavior of reinforced concrete remains elusive, with many conflicting

† Professor
‡ Assistant Professor

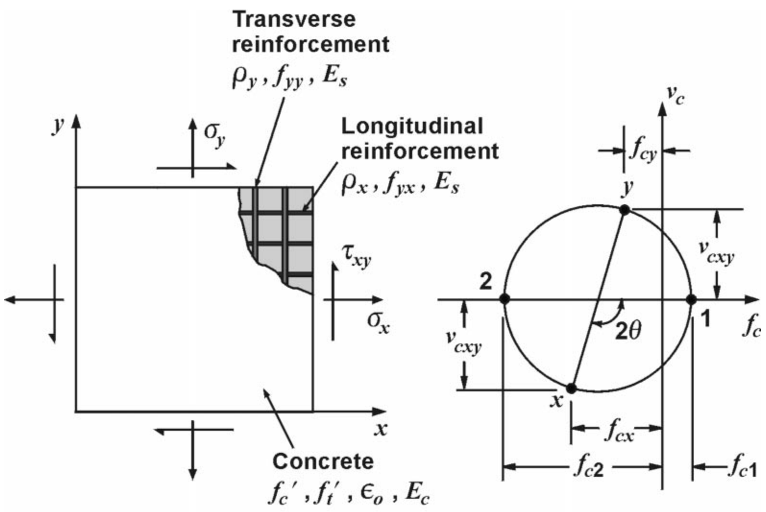
theoretical approaches and constitutive formulas being advanced. NLFEA models and procedures remain complex and limited in range of application, and fraught with various dangers in their proper use (Vecchio 2001).

One modeling approach that has been found to provide accurate simulations over a wide range of conditions is the Modified Compression Field Theory (MCFT). The theory is simple and transparent in its formulation and readily adaptable to complex analysis algorithms. This paper will provide a discussion of forensic analysis capabilities afforded by MCFT-related procedures.

2. Modified compression field theory

The theoretical foundation for the analytical tools presented herein is the Modified Compression Field Theory (Vecchio and Collins 1986). The MCFT is a smeared, rotating crack model describing the load-deformation response of reinforced concrete elements subjected to general two- or three-dimensional stress conditions, as shown in Fig. 1. Conditions of equilibrium, compatibility and constitutive response are formulated in terms of average stresses and average strains; also central to the formulation, however, is the consideration of local stress conditions at crack locations. Concrete is treated as an orthotropic solid continuum with evenly distributed (smeared) cracks, as opposed to a solid interrupted by discrete physical discontinuities. The smeared cracks freely reorient, remaining coaxial with the changing direction of the principal concrete compressive stress field. As well as being computationally convenient, the smeared rotating crack approach is consistent with the distributed and meandering crack patterns observed in many reinforced concrete structures.

In the basic form of the MCFT, the following assumptions are made: reinforcement (permissible in any direction) is well distributed; cracks are uniformly distributed and fully rotating; element boundary stresses are uniformly applied; a unique stress state exists for each strain state, without consideration of strain history; strains and stresses are averaged over distances that include several



(a) Reinforcement and loading conditions

(b) Mohr's circle for average stresses in concrete

Fig. 1 Reinforced concrete element

cracks; concrete principal strain and principal stress directions coincide; perfect bond exists between reinforcement and concrete; independent constitutive relationships can be defined for concrete and reinforcement; and negligible shear stresses exist in the reinforcement. These assumptions lead to a simple and powerful conceptual model that can be applied to a wide range of practical problems. A full description of the formulation is given elsewhere (Vecchio 1990). In nonlinear finite element analysis (NLFEA) implementations subsequently discussed, formulations are included that allow for discrete modeling of concentrated reinforcement, bond slip, dowel action, and concentrated cracking.

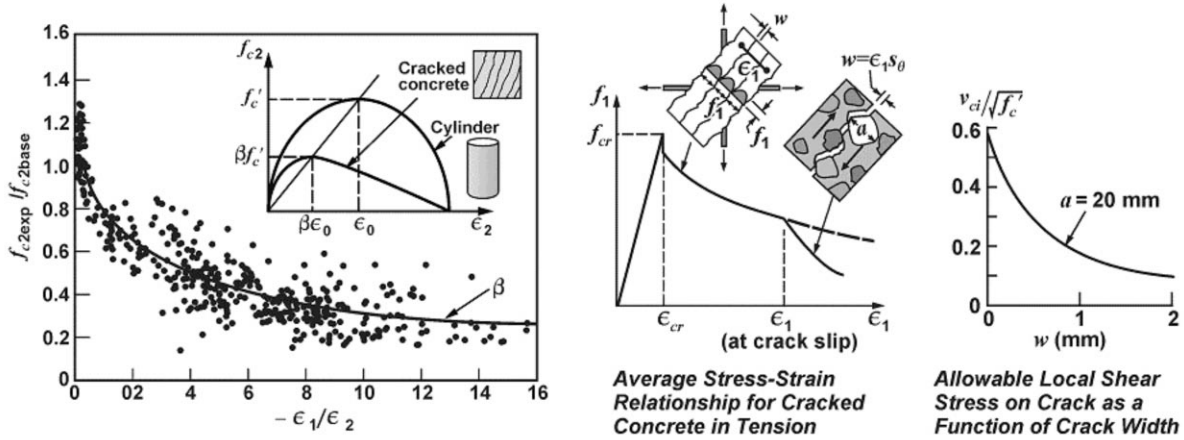
Refinements recently made to the MCFT permit its application to the analysis of confined (uncracked) concrete (Montoya, *el al.* 2001), to structures subjected to general (reversed, cyclic) loading conditions (Palermo and Vecchio 2003), and to repaired, rehabilitated or sequentially constructed structures (Vecchio and Bucci 1999). To permit these enhancements, the effects of load history had to be incorporated into the MCFT formulation. As well, the Disturbed Stress Field Model (DSFM) was recently introduced as a further enhancement (Vecchio 2000). The DSFM removes the restriction that the concrete principal stress and principal strain fields remain coincident, allowing for partial slip along crack surfaces, and hence representing a hybrid formulation between fully-rotating and fixed-crack models. The DSFM provides improved representation of behaviour in lightly-reinforced elements or in structures where response is heavily influenced by large, widely-spaced cracks.

3. Determination of constitutive response through experiment

A significant factor in the ability of the MCFT to accurately represent the behaviour of reinforced concrete elements is that realistic constitutive relations are used, derived from a series of comprehensive test programs. In the MCFT formulation, cracked reinforced concrete is treated as distinctly different from plain uncracked concrete, with both the compression and tension responses affected.

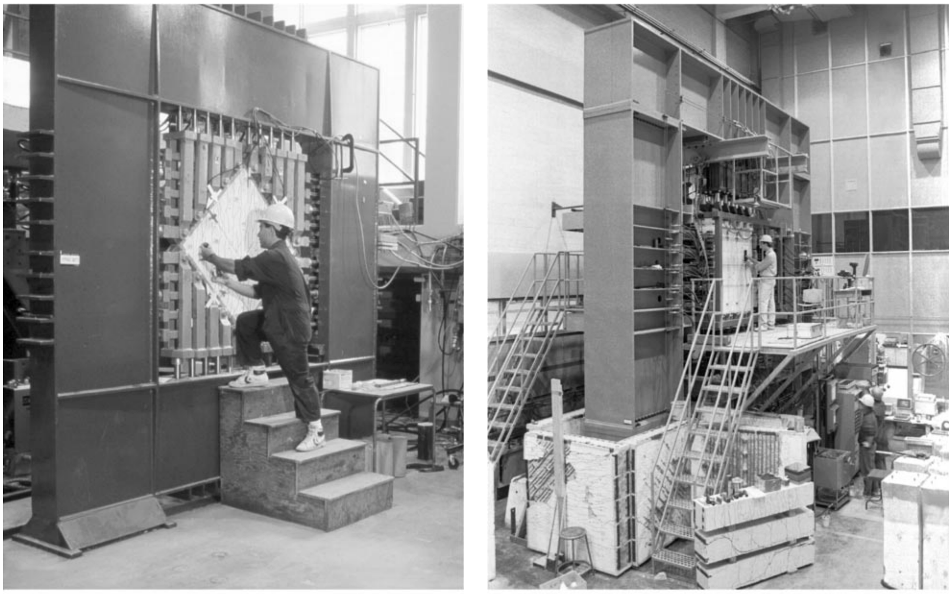
The compression softening relationship employed reflects the observation that cracked compressed concrete, when simultaneously subjected to high tensile strains in the direction normal to the compression, exhibits significantly reduced strength and stiffness relative to uncracked uniaxially-compressed concrete (see Fig. 2(a)). Additionally, a tension stiffening formulation is used to represent the presence and influence of the post-cracking average tensile stresses in the concrete between cracks, developed through bond action with the reinforcement (see Fig. 2(b)). At crack locations, the interface shear stress capacity of the concrete, derived from aggregate interlock mechanisms, is considered. For the reinforcement, the bare-bar stress-strain relationship is used, but the influence of locally increased stresses and strains at crack locations is considered.

The original formulation of the MCFT constitutive models (Vecchio and Collins 1986) was based on a series of 30 panel tests performed in the Panel Element Tester (see Fig. 3(a)). This unique apparatus permitted, for the first time, the testing of panel specimens to general in-plane loads under uniform and well-controlled conditions. Subsequently, the Shell Element Tester (see Fig. 3(b)) was developed to extend testing capability to include general out-of-plane loading conditions as well. Since the initial formulation of the MCFT constitutive models, over 200 additional specimens have been tested using the Panel Element Tester and Shell Element Tester. Only minor modifications to the original constitutive models were necessary as a result of the greatly expanded database. Again, a full description of the MCFT constitutive models is given elsewhere (Vecchio 2000).



(a) Compression softening response (b) Tension stiffening response

Fig. 2 MCFT constitutive modeling of cracked reinforced concrete



(a) Panel element tester (b) Shell element tester

Fig. 3 Testing of panel specimens

4. Development of computer-based analysis tools

Subsequent to the formulation of the basic theory, work was undertaken to implement the MCFT into various design code procedures and advanced analysis tools. A general design method was developed by Collins, *et al*. (1996), which simplified the application of the theory to design of beam elements. Concurrently, various nonlinear finite element analysis (NLFEA) procedures were developed incorporating the conceptual models and constitutive relations of the MCFT.

The **VecTor** suite of NLFEA programs allows the application of the MCFT to a diverse range of structure types including beam sections, two-dimensional membrane structures, three-dimensional solid structures, plates, shells, plane frames, and axisymmetrical solids. The computation approach employed is one based on a secant stiffness formulation using a total-load iterative process; the result is a numerically robust and stable procedure with good convergence characteristics. The secant stiffness approach has been generalized to allow the consideration of arbitrary load histories including reversed cyclic loading conditions (Palermo and Vecchio 2003). In application to forensic analysis, by far the most useful program in the suite has been **VecTor2**, which is suited to the analysis of two-dimensional membrane structures. It seems that the majority of analysis situations encountered can realistically be represented as two-dimensional planar structures; included would be most beams, columns, joint details, one-way slab strips, shear walls, and frame assemblies.

Program **FormWorks** is a graphics-based pre-processor for the Microsoft Windows environment, used in conjunction with the **VecTor** programs (Wong 2002). **FormWorks** includes facilities for data visualization and input, bandwidth reduction and automatic mesh generation. The latter requires only economical user input, permits a high degree of user control over mesh topology, and generates mixed element type meshes for reinforced concrete structures. Hence, the modeling of structural details, reinforcement details, and variable material properties is greatly facilitated.

Program **Augustus** is a graphics-based post-processor for the Microsoft Windows environment,

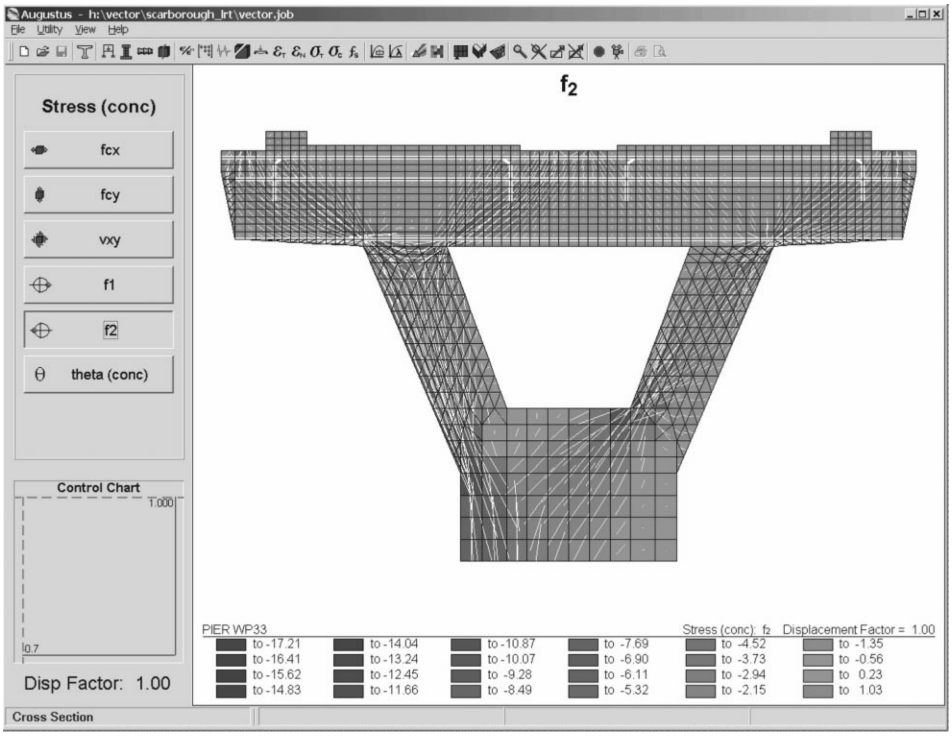


Fig. 4 Program Augustus view of elevated guideway support structure showing principal compressive stresses

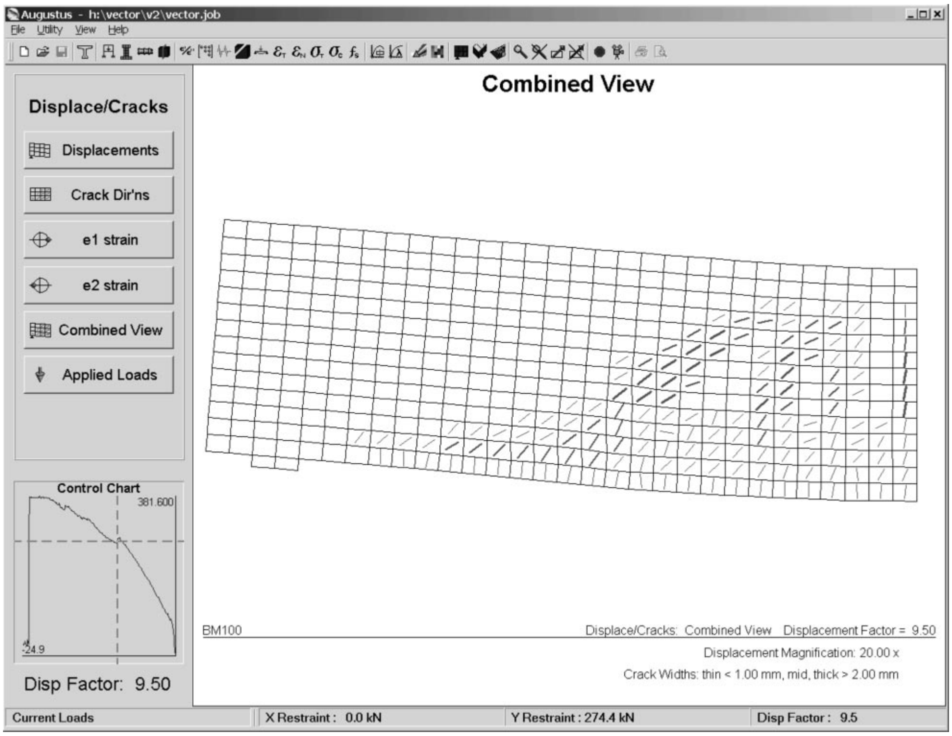


Fig. 5 Augustus representation of crack pattern and deflected shape in beam with stirrups

also meant for use with the **VecTor** programs. It provides comprehensive post-analysis visualization of global and local load-deformation response, element stress and strain conditions, deflection and crack patterns, damage indicators, and other pertinent data (e.g., see Figs. 4 and 5). It has been found from experience that the provision of proper post-processing facilities is critical to producing accurate and error-free analyses.

Program **Response-2000** provides enhanced modeling and analysis capabilities for beam elements, using a layered section analysis approach (Bentz 2000). In addition to the traditional abilities of a sectional model to account for the effects of axial load and shear, Response-2000 also allows rigorous inclusion of the effects of shear. Thus shear-moment-axial load interaction effects on strength and ductility are automatically taken into effect. The program is based on the assumption of plane sections remaining plane, zero clamping stress through the depth of the beam and the constitutive relations of the MCFT. Example capabilities are illustrated in Figs. 6 and 7.

Demonstration versions of **VecTor2** and **FormWorks** can be freely downloaded from:

www.civ.utoronto.ca/vector/

Demonstration versions of **Augustus** and the full version of **Response-2000** can be obtained from:

www.ecf.utoronto.ca/~bentz/

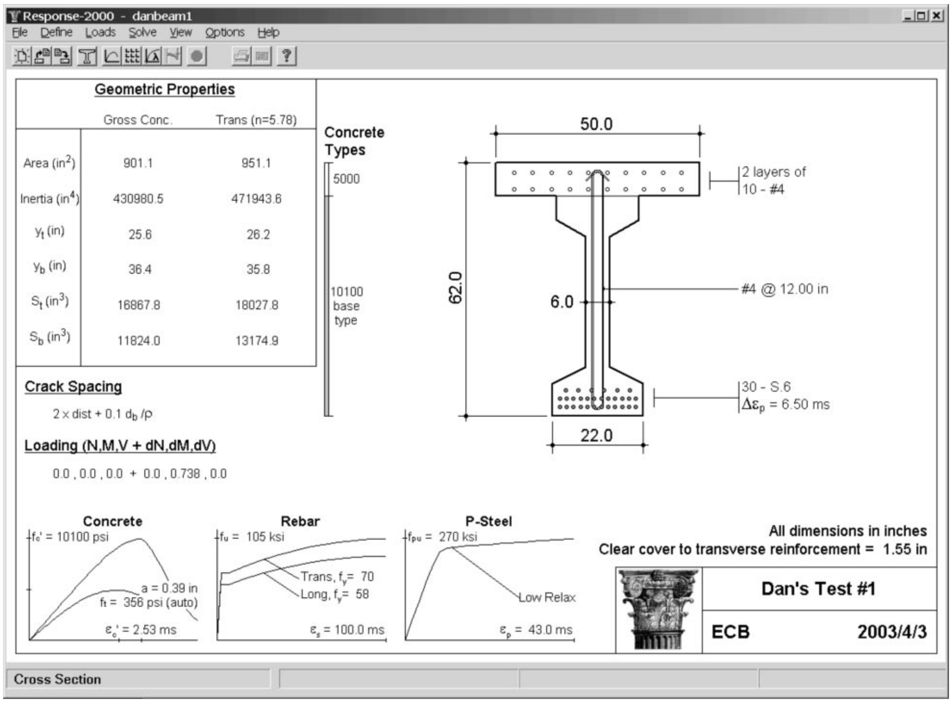


Fig. 6 Automatically produced cross section of beam from Response-2000 (US Units)

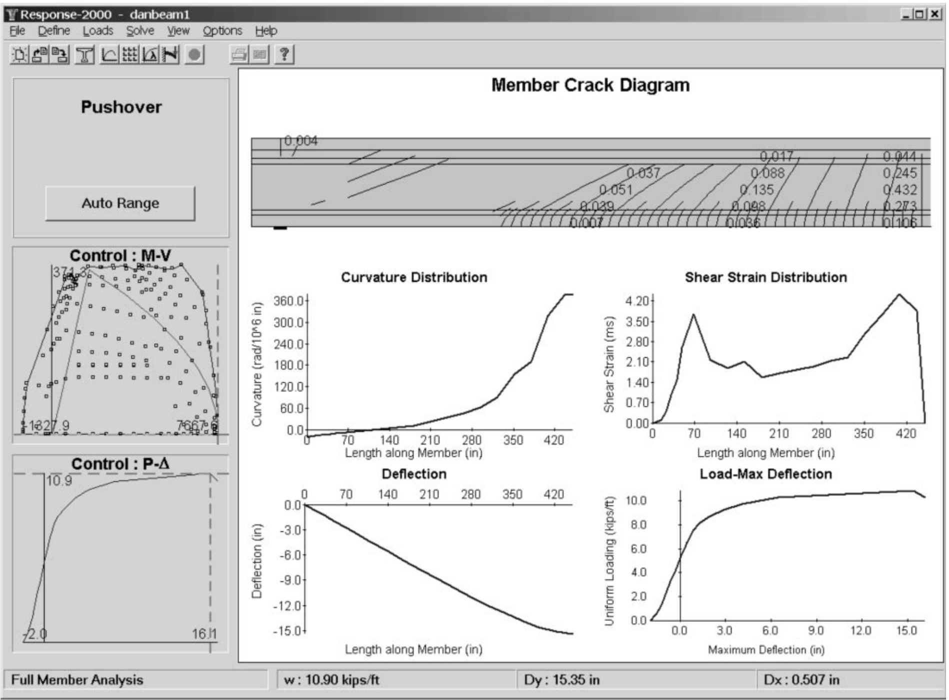


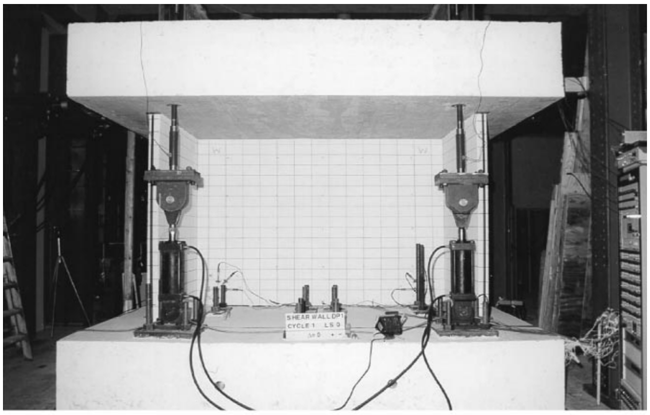
Fig. 7 Response-2000 results from an analysis of a prestressed concrete beam

Note that the demonstration version of VecTor2 is limited to 500 elements. Also note that the authors accept no responsibility for the proper use or accuracy of these programs.

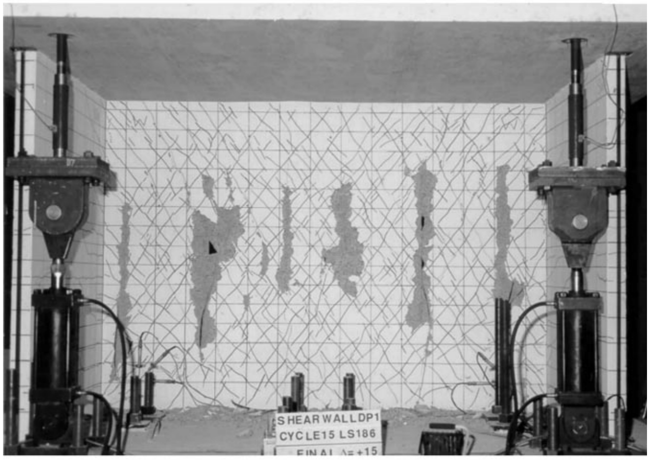
5. Corroboration with test results

An integral part of the methodology needed in the development of reliable analysis tools is the use of realistic large-scale test specimens to corroborate theoretical models and computational procedures. Often, the test specimens and loading conditions must be specifically configured to reveal the nature and influence of a particular behaviour mechanism. From the results of such large-scale test specimens, deficiencies in theory or computational process can be uncovered and the formulations refined accordingly.

The development of the MCFT was supported by a comprehensive program of large-scale testing, over a period of 25 years, at the University of Toronto. Various test programs have involved two-storey frames, strip-slab-and-column subassemblies, flat slabs subjected to thermal loads, cylindrical

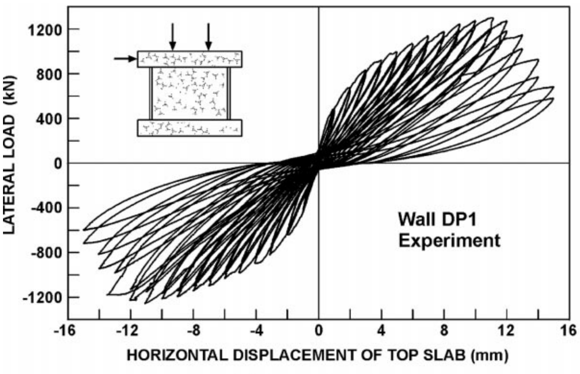


(a) Prior to testing

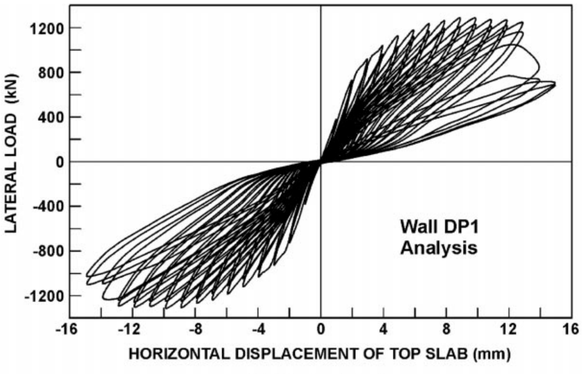


(b) After web shear failure

Fig. 8 Flanged shear wall specimen DP1



(a) Experiment



(b) Calculated

Fig. 9 Lateral load-deflection response of DP1

shells subjected to hydrostatic loads, three-dimensional shear walls, and beams and columns of various description. Comparisons of observed-to-calculated behaviour have shown the MCFT to provide accurate simulations of response over a wide range of structural types and loading conditions (e.g., see Vecchio, Polak and Selby 1996).

An example of such a corroboration study involved the testing of large-scale flanged shear walls subjected to various combinations of axial and lateral load (Palermo and Vecchio 2002). Specimen DP1, shown in Fig. 8(a), was subjected to constant axial loading and reversed cyclic lateral displacements of increasing amplitude. Eventually, the wall sustained a web shear failure marked by the formation of several vertical shear planes (see Fig. 8(b)). The measured lateral-load deformation response is given in Fig. 9(a).

An analysis of the expected response of the wall was performed using **VecTor2**; the computed load-deformation response is given in Fig. 9(b). Reasonably good correlation was obtained in terms

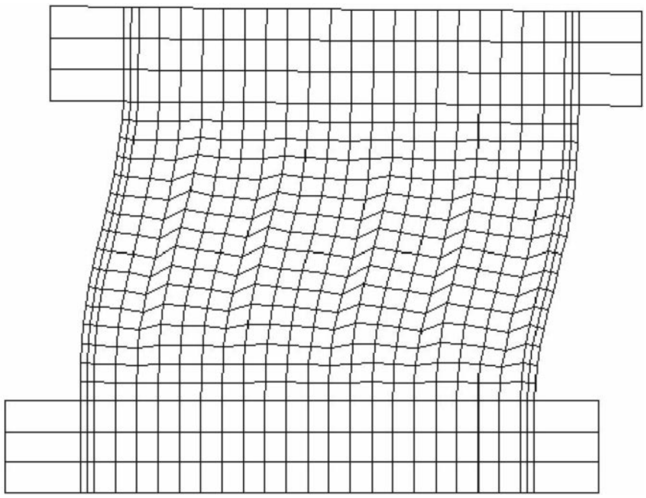


Fig. 10 Predicted failure mode for DP1, calculated from VecTor2

of pre- and post-cracking stiffness, ultimate load capacity, deflection at ultimate strength, post-peak ductility, and energy dissipation per loading cycle. Moreover, as seen in Fig. 10, the unusual failure mode was also well-predicted. Such a degree of accuracy in the modeling, to within 5 to 10% of experimentally observed values, is typical.

Hence, the computational tools have been extensively tested against the results of large-scale test specimens representing details and loading conditions commonly found in actual structures. The results of this program of comparison testing have provided a good measure of confidence regarding the accuracy and appropriateness of the underlying theories and procedures.

6. Application to forensic analysis

When engineers are confronted with a structure in distress, the application of forensic tools such as **VecTor2** can be very helpful in determining potential problems. As shown below, such investigations will generally require multiple tools of varying levels of complexity coupled with sound engineering judgment.

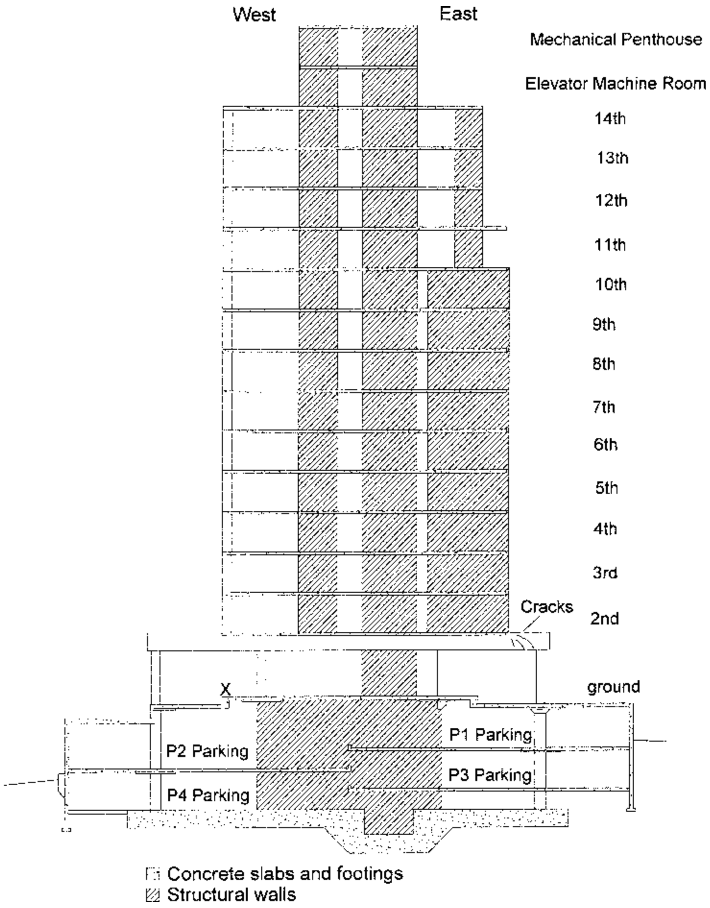


Fig. 11 Structure in distress in Toronto area. Note cracks in transfer beam on right side of structure, 2nd floor

A four-year-old building in the Toronto area was noticed to be suffering from significant cracking in large transfer beams near the entranceway. A cross section of the building is shown in Fig. 11. Note the location of cracking on the 2nd floor transfer beams on the right side of the building. After appropriate site inspections and examination of the drawings, it was determined that the structure was built on a relatively flexible raft foundation on a large layer of clay. It was determined that differential soil settlement was likely important to the structural behaviour, and that it would take perhaps ten years before the structure had achieved maximum settlement into the soil and stabilized.

To quantify the effects of the soil-structure interaction and determine the overall moment shear and axial load demands on the structure, a **RUAUMOKO** analysis was performed on the structure. This nonlinear time-history frame analysis program from New Zealand allows the inclusion of the effects of shear walls and simple soil-structure interaction (Carr 2002). Fig. 12 shows the simplified structural model used for the nonlinear frame analysis. A certain amount of iteration was required in the creation of this model to ensure that the correct amount of complexity was provided. As just

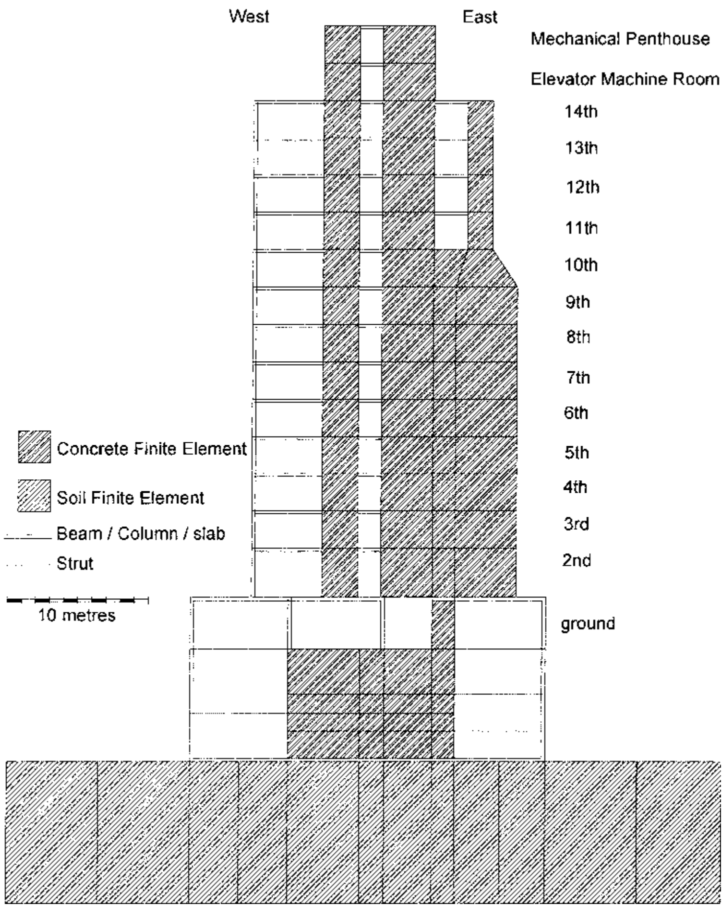


Fig. 12 Simplified structural model of structure for use with RUAUMOKO nonlinear analysis package

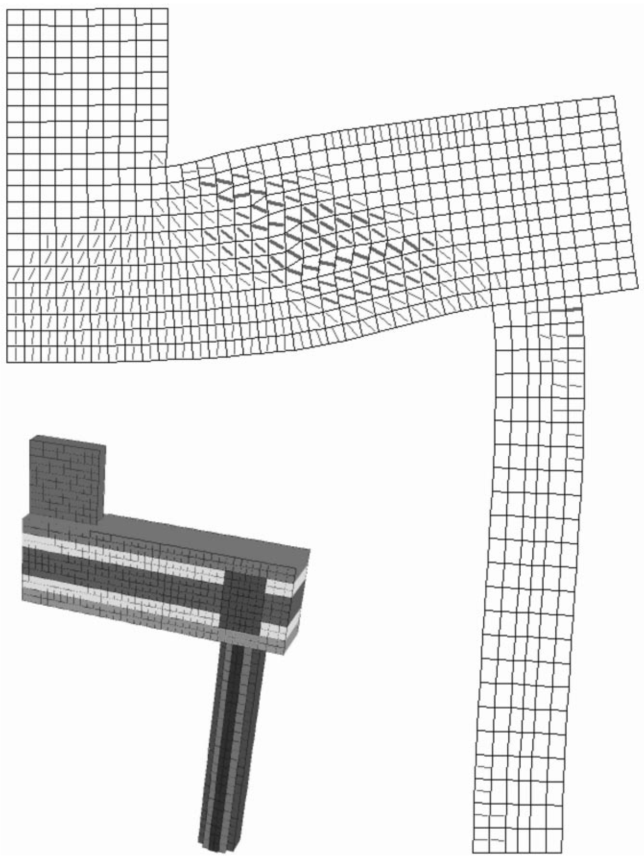


Fig. 13 Predicted crack pattern in beams near right side of transfer beams, obtained from VecTor2 analysis. Deflection magnified 50 times

one example, the discretization of the transfer beam near the elevator core required two coincident nodes with some degrees of freedom slaved together to account for cracking that would decouple the rotational degree of freedom of the transfer beam from the elevator core. Over 50 analyses were performed with **RUAUMOKO** to determine the combined effects of wind and dead load with varying soil stiffness properties. These analyses demonstrated that the structure was indeed suffering from substantial differential settlement, a fact later confirmed with surveys of the foundation slab.

With the global moments, shear forces and axial loads, it became possible to create a local model for use with **VecTor2** that showed the behaviour of the highly cracked beams near the entranceway. Fig. 13 shows the predicted crack pattern at shear failure with displacements magnified 50 times. The results of the local analysis compared to the loads from the global analyses indicated that these beams were grossly under-designed and would suffer very low safety factors once the structure had completed settling. Shear strengthening of the beams with carbon fibre wraps was ordered and implemented.

As an example of the power and value of easy-to-use forensic tools, such as **VecTor2** and **Response-2000**, it was considered prudent and practical to perform one final local analysis of part of this structure at the last minute. In preparation of the final report on the previous analyses, it was

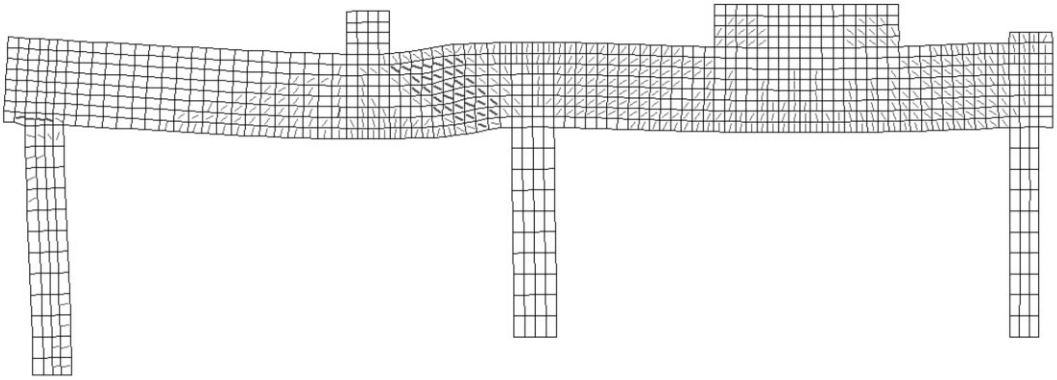


Fig. 14 Predicted crack pattern in beams near left side of transfer beams

noted in the structural drawings that an unusual reinforcing detail had been used on the left hand side transfer girders of the building, quite separate from the problems with the beams at the entranceway. As these beams were hidden behind drywall, they were not noted to be a concern by the owners or previous engineering firms that examined the building. An analysis was performed on this part of the structure, again using the loads from the global analysis of **RUAUMOKO**. This part of the structure was loaded primarily with dead load and was not strongly affected by the settlement of the building. Fig. 14 shows the cracking patterns at a load level 1.25 times the unfactored applied dead load, immediately before a shear failure in the short shear span. Clearly a safety factor of 1.25 is dangerously unsafe when resisting a large dead load by a brittle shear mechanism. At an inspection the next day, after removal of the drywall, large cracks were found in the beam that were worse than the cracks over the entranceway that had been the cause of the entire analysis to be performed in the first place. A temporary repair was made to support this part of the building that has now been replaced with a permanent column down to the raft foundation at the location of the "X" in Fig. 11.

Throughout the process of performing these analyses, it was found that clear and easy to use post-processing facilities were critical in determining the true safety of this structure. On three separate occasions, significant errors were made in the modelling that likely would have gone unnoticed were it not for the use of colored plots that encouraged detailed examination of all results. A second conclusion from these analyses is that the initial linear analysis of this structure was of essentially no use. Elastic analyses indicated that the forces in the transfer beams should have been so large that the structure would already have collapsed. It was only through the use of nonlinear analysis that feasible explanations were found for why the structure showed the observed damage, where unknown damage existed, and where repairs were necessary.

7. Conclusions

The Modified Compression Field Theory provides a powerful, accurate platform for forensic assessment of distressed or failed reinforced concrete structures. A suite of computer-based analysis tools have been formulated accordingly. Experiences in their use suggest the following observations:

1. In most cases, it is possible to make a reasonably accurate assessment of the load capacity and

failure mode of a distressed or failed structure.

2. The analysis tools are useful in identifying critical factors, details, and behaviour mechanisms influencing the safety and performances of the structure.
3. The tools are also useful in investigating alternative design details or alternative retrofit/repair schemes.
4. Conventional analysis procedures (for example, linear elastic analyses) are sometimes wholly inadequate in capturing the influence of critical mechanisms, and may lead to gross errors in assessment.
5. Good quality post-processing facilities are critical to ensure correct modeling, interpretation and understanding of structural problems.

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