Nonlinear Finite Element Program for Reinforced Concrete Structural Control

Tawanda. Mushiri Member, IAENG, Wilson R. Nyemba, and Charles. Mbohwa

Abstract— **Proprietary softwares are often used for structural control in engineering. Nonlinear structural control researches often uses nonlinear finite element toolbox (NLFET) code which was specifically developed for coding and simulations of structures. This paper provides an overview of the use of NLFET including the data structures and algorithms used to develop a nonlinear finite element program for reinforced concrete structural control. In order to make use of the nonlinear routines, powerful control and NLFET toolboxes, NFLET are implemented in MATLAB. The data of the structure is stored in MATLAB structures for maximum flexibility and to improve the readability of the code. Object oriented design is used to define element types so that new elements (both linear and nonlinear) can be added easily and without necessitating changes in the core analysis code. Solidworks was the software in this paper.**

Index Terms— **Solidworks, Finite element analysis, structural analysis, control, earthquake, fire, NLFET toolbox, reinforced concrete**

I. INTRODUCTION

The main aspects of numerical modelling process to simulate blast loads, structural geometries and material behaviour are addressed (Beshara F.B.A, 1991). Numerical stability has been controlled using appropriate time increments and energy balance check. Nonlinear finite element analysis helps researchers to conduct more detailed investigations on the behavior of reinforced concrete structural elements (BĂETU S and CIONGRADI I.P, 2011). Reinforced concrete walls are important structural elements that are placed in multistorey buildings from seismic zones, because they have a high resistance to lateral earthquake loads. Reinforced concrete structural walls must have sufficient ductility to avoid brittle failure under the action of strong lateral seismic loads. For the design of a ductile structural wall it is desirable that yielding of flexural reinforcement in plastic hinge region, normally at the base of the wall, would control the strength, inelastic deformation and energy dissipation (BĂETU S and CIONGRADI I.P, 2011).

A. DEFINITION OF THE PROBLEM

Earthquake and fire has caused more harm than good in multistorey buildings to fail.

B. AIM

To develop a non-linear finite element program for ease numerical simulations for vibration control of reinforced concrete structures using Solidworks and Matlab.

II: LITERATURE SURVEY

The issue of storey buildings is affected by many effects in their strength. Earthquake and fire are disastrous more often. Fire is one of the extreme loadings that can act on reinforced concrete structures. The need to incorporate this extreme loading into structural design has long been recognized, and the traditional design method for structural fire resistance has been widely practiced by engineers mainly because of its simplicity.

A. FIRE PREVENTION

However, the investigation of the World Trade Centre disaster by the BPAT (Building Performance Assessment Team) indicated that the fire issues were most crucial in the collapse of the twin towers (Kodur V, 2003). Other than that, reinforced concrete structures are commonly exposed to thermal loads as the result of the design function of the structure, ambient conditions, heat of hydration, or exposure to fire (Vecchio F.J.; Agostino N.; and Angelakos B., 1993). Heat transfer is concerned with the physical processes underlying the transport of thermal energy due to a temperature difference or gradient. Conservation principles of mass, momentum, and

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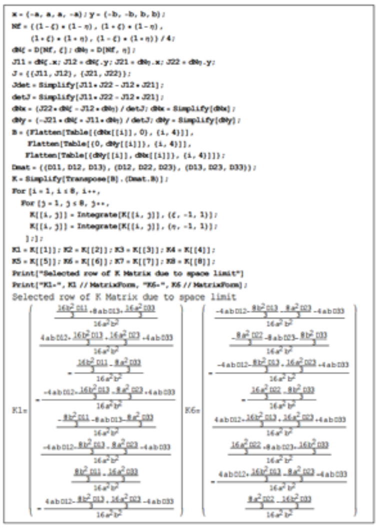
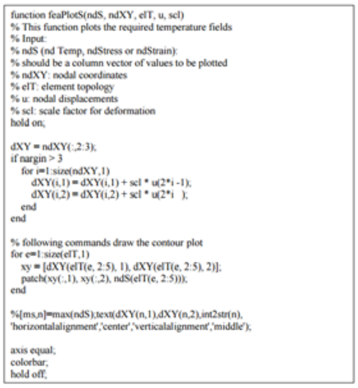
energy always lead to differential equations (in a more general sense, integral equations). Because of those complex mathematical equations, numerical methods are usually preferred, instead of solving problems analytically (Cheng En Zhou, 2004). Figure 1 shows how the author approached the fire prevention on fire using Mathematica.



```
x = {-a, a, a, -a}; y = {-b, -b, b, b};
Nf = {(1 - ξ) * (1 - η), (1 + ξ) * (1 - η),
     (1 + ξ) * (1 + η), (1 - ξ) * (1 + η)} / 4;
dNξ = D[Nf, ξ]; dNη = D[Nf, η];
J11 = dNξ.x; J12 = dNξ.y; J21 = dNη.x; J22 = dNη.y;
J = {{J11, J12}, {J21, J22}};
Jdet = Simplify[J11 * J22 - J12 * J21];
detJ = Simplify[J11 * J22 - J12 * J21];
dNx = (J22 * dNξ - J12 * dNη) / detJ; dNx = Simplify[dNx];
dNy = (-J21 * dNξ + J11 * dNη) / detJ; dNy = Simplify[dNy];
B = {Flatten[Table[{dNx[[i]], 0}, {i, 4}]],
    Flatten[Table[{0, dNy[[i]]}, {i, 4}]],
   Flatten[Table[{dNy[[i]], dNx[[i]]}, {i, 4}]]};
Dmat = {{D11, D12, D13}, {D12, D22, D23}, {D13, D23, D33}};
K = Simplify[Transpose[B].(Dmat.B)];
For [i = 1, i ≤ 8, i++,
  For [j = 1, j ≤ 8, j++,
    K[[i, j]] = Integrate[K[[i, j]], {ξ, -1, 1}];
    K[[i, j]] = Integrate[K[[i, j]], {η, -1, 1}];
   ];];
K1 = K[[1]]; K2 = K[[2]]; K3 = K[[3]]; K4 = K[[4]];
K5 = K[[5]]; K6 = K[[6]]; K7 = K[[7]]; K8 = K[[8]];
Print["Selected row of K Matrix due to space limit"]
Print["K1=", K1 // MatrixForm, "K6=", K6 // MatrixForm];
Selected row of K Matrix due to space limit
```

Fig. 1. Rectangle's stiffness matrix calculation in Mathematica (Cheng En Zhou, 2004)

The considerable potential of the Computer Algebra System (CAS), for example Mathematica and Maple, will be further demonstrated when constructing stiffness matrix for a general quadrilateral element. While a code similar to the one shown in Fig. 1 can be used in the derivation, the computation would likely never stop proceeding due to the rational Jacobian involved. In other words, the analytical expression for the fully integrated stiffness matrix of a quadrilateral four-node element does not seem to exist. Based on CAS and under the assumption of an isotropic elastic material (Cheng En Zhou, 2004). Matlab was used to come with the temperature distribution.



```
function feaPlotS(ndS, ndXY, elT, u, scl)
% This function plots the required temperature fields
% Input:
% ndS (nd Temp, ndStress or ndStrain):
% should be a column vector of values to be plotted
% ndXY: nodal coordinates
% elT: element topology
% u: nodal displacements
% scl: scale factor for deformation
hold on;

dXY = ndXY(:,2:3);
if nargin > 3
   for i=1:size(ndXY,1)
      dXY(i,1) = dXY(i,1) + scl * u(2*i -1);
      dXY(i,2) = dXY(i,2) + scl * u(2*i   );
   end
end

% following commands draw the contour plot
for e=1:size(elT,1)
   xy = [dXY(elT(e, 2:5), 1), dXY(elT(e, 2:5), 2)];
   patch(xy(:,1), xy(:,2), ndS(elT(e, 2:5)));
end

%[ms,n]=max(ndS);text(dXY(n,1),dXY(n,2),int2str(n),
'horizontalalignment','center','verticalalignment','middle');

axis equal;
colorbar;
hold off;
```

Fig. 2. Contour plot of the temperature distribution in MATLAB

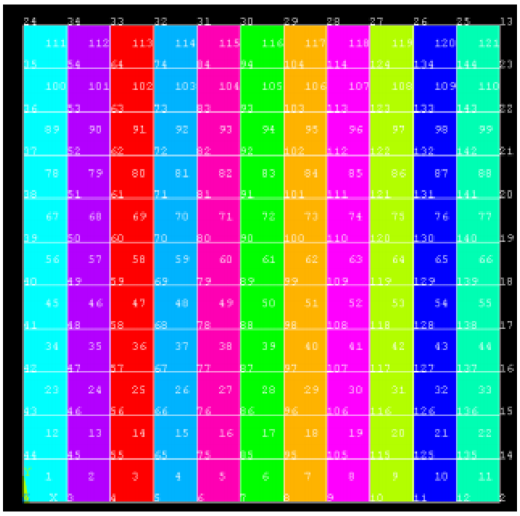


Fig. 3. The finite element model for Problem 1

Figure 3 was drawn by the author to show the finite element model. As shown in Fig. 5.2, a 11´11 uniform computational grid is employed so that there are 12´12 = 144 nodes within the model. The model will be analyzed through 100 time steps of 50s duration, with a maximum of 100 iterations allowed at each time step. The criterion for convergence of iterative computations is prescribed to be 1.0×10^{-5} (Cheng En Zhou, 2004)

. In this work, a 2D transient nonlinear thermal analysis capability is implemented into program VecTor2. Models are created to account for the time-varying thermal loads and the temperature-dependence of the various concrete and steel mechanical and thermal properties that influence structural and thermal analyses. In addition, formulations for considering heat-of-hydration problems and algorithms for calculating the closed-form element stiffness for a quadrilateral element with a fully-populated material stiffness are developed and realized. With the results obtained from numerical corroboration testing, the developed computational scheme and the implemented code are found to be accurate, stable and reliable. However, considerable improvements are required before they equal the prominence of the static and dynamic analyses within the VecTor suite of program development and in the advanced concrete structural analysis (Cheng En Zhou, 2004). Load curve was obtained as shown in figure 4.

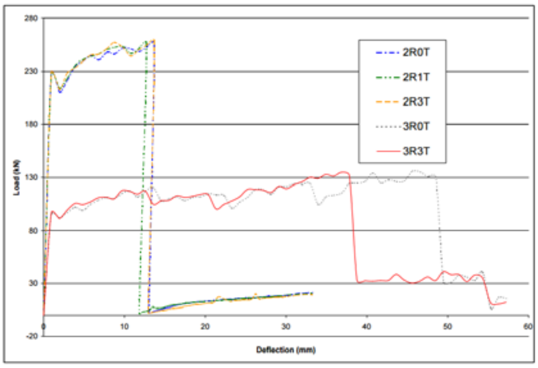


Fig. 4. Load-deformation curves obtained in Type test (Cheng En Zhou, 2004).

B. ANALYSIS OF STRUCTURES WITH ANSYS

Structural reinforced concrete walls represents a system that provides lateral resistance, high stiffness and strength to a building. Because the energy dissipation is made only by the base of the structural walls, they do not exhibit ductile and redundant behavior. The structural reinforced concrete wall energy dissipator, named and structural slit wall with shear connections, remove some of the problems encountered with ordinary structural walls. Yielding of shear connections in this wall may cause increase in energy dissipation, forming a structural damper that is based on structural passive control (BĂETU S and CIONGRADI I.P, 2011). The multilinear isotropic stress–strain implemented curve requires that the first point of the curve to be defined by the user, this must satisfy Hooke’s law as shown below.

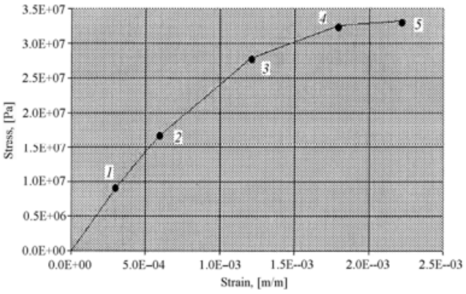


Fig. 5. Uniaxial stress–strain curve for concrete C20/23

Implementation of the Willam and Warnke material model in ANSYS requires different constants to be defined as shown in table 1 (BĂETU S and CIONGRADI I.P, 2011).

TABLE I
CONCRETE CONSTANTS

1	Shear transfer coefficients for an open crack (βt)	0.4
2	Shear transfer coefficients for an closed crack (βc)	0.8
3	Uniaxial tensile cracking stress (fr)	2E+006 Pa
4	Uniaxial crushing stress (fc)	3.33E+007 Pa
5	Biaxial crushing stress	0
6	Ambient hydrostatic stress state for use with constants 7 and 8	0
7	Biaxial crushing stress under the ambient hydrostatic stress state	0
8	Uniaxial crushing stress under the ambient hydrostatic stress state	0
9	Stiffness multiplier for crack tensile condition	0

The strain as well was shown by the two authors using ANSYS

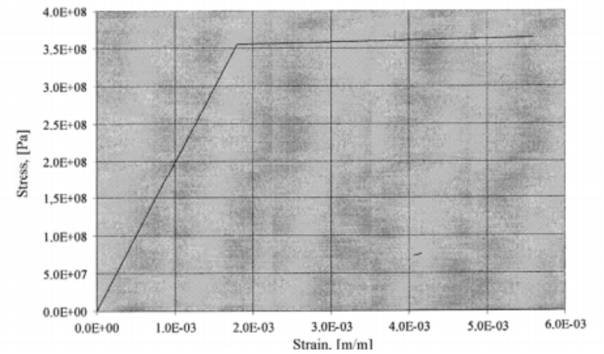


Fig. 6. Stress–strain curve for reinforcement in ANSYS model (BĂETU S and CIONGRADI I.P, 2011).

The finite element model was also done as shown below.

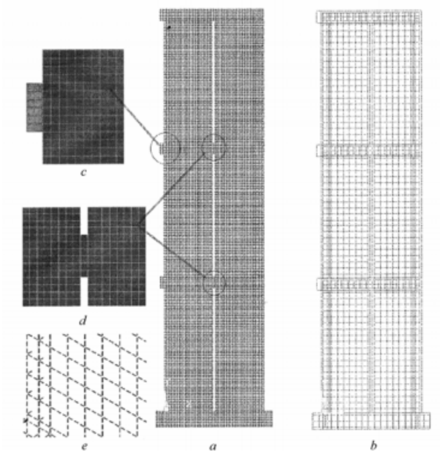


Fig. 7. Finite element model: a – concrete Solid 65, b – reinforcement Link 8, c – detail of loading zone, d – details of connections, e – 3-D detail of reinforcement arrangement (BĂETU S and CIONGRADI I.P, 2011).

The finite element model was modelled by these authors in this report. Comparisons between pushover curves shows that slit walls and solid walls have a similar behavior until shear connectors start to crush.

As the cracks on shear connections increase we can observe that the rigidity of the wall decreases and the structural walls split in two forming in this way two flexible solid walls in each case analysed. An important observation is that applicability of this solution for energy dissipation is more pronounced for tall structural walls from high-rises buildings, where the predominant effort is a bending one. The wall must be sufficiently slender so that the slipping along the connections zone to appear before cracks from the wall base become dangerous (BĂETU S and CIONGRADI I.P, 2011). An economical design of buildings based on performance takes into account the dissipation of seismic energy accumulated in the structure. Reinforced concrete walls are frequently used as strength elements for structures designed in areas with high seismic risk. The fact is, in a tall structural wall, plastic hinge formation happens only at the base of the wall and ductility resources of the rest of the wall remains untapped (BĂETU S and CIONGRADI I.P, 2011).

C. STRESS AND CREEP IN FAILURE OF STRUCTURES

Bailey is the pioneer in the study of design aspect of creep; in 1935 he proposed general expression for creep in terms of principal stresses based on simple tension test ((Bailey, 1935) (Riordan, 2006). Bailey did many several to verify the validity of those general creep expressions and got good agreement. Satisfactory estimate of a correlation of tension creep test with relaxation tests was made by Popov in his PhD dissertation work (Popov, 1947). The validity of methods for simple relaxation is demonstrated on the bases of experimental agreement between calculated and test results. The formulations for tension creep curves were established. Then the analytical schemes that appear satisfactory are extended for relaxation with the elastic follow-up.

The consideration of primary creep in the design of internal-pressure vessels was proposed by Coffin et al (Coffin, 1949). In their paper the evaluation of permanent strains and stresses at a particular time resulting from loading a thick-walled cylinder under constant internal pressure and elevated temperature when account is taken to the primary creep characteristics of a given material. The results are compared with permanent strains obtained by considering secondary creep as the general bases for pressure vessel design. Till then the commonly accepted bases for design of pressure vessel at elevated temperatures has been by the use of tensile secondary-creep data applied to combine steady stress such as the method used by Bailey (Bailey, 1935). They show how the tensile primary creep characteristics may be utilized in the design of thick-walled pressure vessels. In other words, they showed the stress-deformation history of the tube from the time when the pressure is applied initially until its life expectancy, or to the time when steady-state Conditions corresponding to secondary creep are reached. Yoh-han Pao and Marin formulate on analytical theory of creep deformation of materials (Popov, 1947). The theory was proposed for idealized materials and may be applied to those materials whose behavior conforms to that idealized material. In the theory, the initial elastic strain, the transient creep strain, and the minimum rate creep strain are taken to account. Creep analysis of axisymmetric bodies using finite elements for calculating the creep strains was developed by Greenbaum and Rubinstein (Popov, 1947). The method involves starting with the elastic solution of the problem and calculating the creep strains for a small time increment. Those creep strains for a small time increment. Those creep strains are treated as initial strains to determine the new stress distribution at the end of the time increment. Next an outline of some of the available literatures from 1975 to date was done. Lower bounds on rupture times of thick-walled tube in pure torsion and a hollow sphere under constant internal pressure were obtained by Goel and numerical values of rapture time for the tube case with different forms of damage rate lows were presented (ASME, 1918).

The type of damage law assumed makes a significant effect on predicting the time to rapture but failure in all cases occurs almost instantaneously after the appearance of first crack. A structural element in creep may rupture in any of the two modes of failure, namely, ductile and brittle. When a structural component is subjected to high stress levels failure may occur due to the geometric instability caused by necking; such a failure is called ductile failure. On the other hand, structures at low stresses and high temperatures may exhibit brittle failure. It happens due to the degradation of the microstructure of the material. Fissures and voids are usually found where such a failure occurs and these voids and fissures grow on planes which are perpendicular to the direction of the maximum principal stress.

When metals are subjected to stress at temperatures in excess of $0.33mT$ where $m\ T$ is the absolute melting temperate, the metal suffers time-dependent creep deformations (Gateway, 2014). In addition, internal damage increases with time and ultimately the metal ruptures. Therefore, when designing shell structures operating at such evaluated temperatures, consideration must be made to ensure that creep deformations do not exceed operational requirements during the life of the component (Popov, 1947). There are six major groups into which all tube failures can be classified. These six groups can be further divided in to a total of twenty-two primary types. All high pressure boilers commissioned and put into operation go through a stabilization period, during which some teething problems occur, including a few tube failures.

D. NONLINEAR FINITE ELEMENT ANALYSIS IN LARGE SCALE

The accuracy of large scale elements in nonlinear finite element analyses (NLFEA) of reinforced concrete is investigated. A much used finite element analysis design procedure, used to design large offshore concrete structures, is presented, and suggestions for the utilization of NLFEA in the process is given. Means to obtain effective use of NLFEA are discussed and the importance of large elements to minimize the computational cost is stressed. The use of large elements is investigated in a case study of a structural wall. The wall is analyzed using medium scale elements that should be able to predict the behavior well, and by use of large elements. Both analysis results are compared with experimental results. The finite element models are created as they would in a design situation and the analyses are conducted without tweaking of the material parameters.

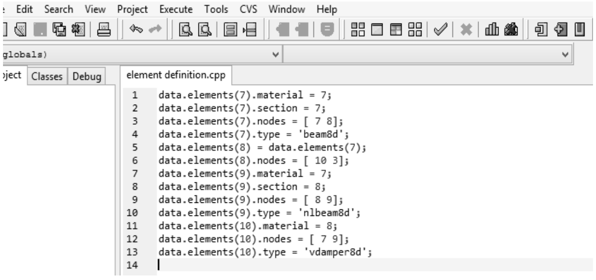
State-of-the-art material models, that accurately describe the most important material characteristics of reinforced concrete, are selected. A short presentation of the smeared crack approach for finite element modeling of concrete is given. Both a fixed and a rotating crack model is used (Pettersen J.S, 2003).

III: METHODOLOGY

The structures were modeled by Matlab and Solidworks in this case. After going through the literature review to understand on how the development of cracks in structures, fire, earthquake and creep are the most affecting failure of buildings. In this research, the design is focusing on eliminating these failures.

IV: RESULTS AND DISCUSSION

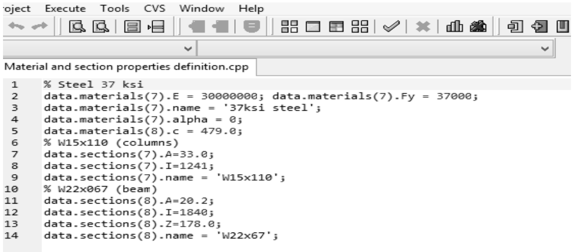
Figures below show the simulations and how failure maybe reduced.



```
data.elements(7).material = 7;
data.elements(7).section = 7;
data.elements(7).nodes = [ 7 8];
data.elements(7).type = 'beam8d';
data.elements(8) = data.elements(7);
data.elements(8).nodes = [ 10 3];
data.elements(9).material = 7;
data.elements(9).section = 8;
data.elements(9).nodes = [ 8 9];
data.elements(9).type = 'nlbeam8d';
data.elements(10).material = 8;
data.elements(10).nodes = [ 7 9];
data.elements(10).type = 'vdamper8d';
```

Fig. 8. Element definition code in NLFET

The program was put in Solidworks and the element definition put forward.



```
% Steel 37 ksi
data.materials(7).E = 30000000; data.materials(7).Fy = 37000;
data.materials(7).name = '37ksi steel';
data.materials(7).alpha = 0;
data.materials(8).c = 479.0;
% W15x110 (columns)
data.sections(7).A=33.0;
data.sections(7).I=1241;
data.sections(7).name = 'W15x110';
% W22x067 (beam)
data.sections(8).A=20.2;
data.sections(8).I=1840;
data.sections(8).Z=178.0;
data.sections(8).name = 'W22x67';
```

Fig. 9. Material and section properties definition code in NLFET

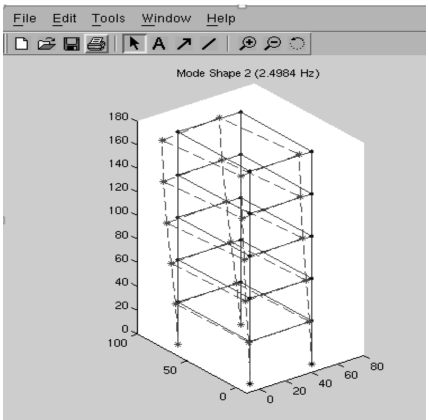


Fig. 10. Mode shape diagram

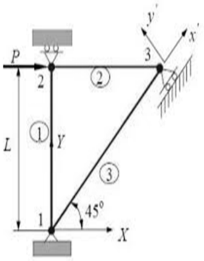


Fig. 11. Diagram of nodes

V: CONCLUSION

The nonlinear finite element toolbox has been developed to ease numerical simulation in structural control. Advantages of this software are the object-oriented design, overall modular architecture, and the availability of the source code. A simple dynamic analysis example has been presented to illustrate the use of NLFET.

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