UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF FINITE ELEMENT CODES FOR SHEAR WALL ANALYSIS

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By

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Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Dedicated to

To my parents

Abstract of thesis presented to the Senate of University Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF FINITE ELEMENT CODES FOR SHEAR WALL ANALYSIS

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Chairman: Associate Professor Jamaloddin Noorzaei, PhD

Faculty : Engineering

Shear wall is commonly employed as a principal element to resist lateral loads due to wind or earthquake forces. An accurate mathematical model for shear wall structure needs to consider the effect of all components in the system i.e. shear wall, foundation, and subsoil. In addition to the necessity for accurate modelling of shear wall-foundation-soil system, the model must be proficient to capture the structural response of the shear wall building-foundation-soil and it should also be computationally efficient. Furthermore, since shear wall is a key structural element which plays a major role to ensure stability of the shear building system under lateral loads, it is essential to consider the inelastic response of the shear wall buildings.

With the tremendous advancement in computer technology several finite element software's are commercially available to researchers and engineers. However, this would not serve the objectives of the research investigator. In this study, new elements have been developed, modified constitutive law has been proposed, new computational algorithm has been utilised.

Furthermore, this investigation focuses on the development of effective and suitable modelling of reinforced concrete shear walls. The modelling includes physical and constitutive modelling.

(a) Physical modelling

Most suitable elements had been adopted and some new elements have been developed for physical modelling of shear wall structural systems. The elements used for the purpose of mathematical discretisation of the shear wall structural system are:

- Modified optimal triangle (MOPT) element with drilling degree of freedom to represent the superstructure and foundation. This element was developed in this study.
- Interface element to represent the interfacial characteristics between the foundation represented by MOPT element with three degree of freedom per node (top continuum) and bottom continuum i.e. soil media idealised as plane stress /plane strain problem with two degree of freedom per node. This element was developed to incorporate slip and separation at the interface.
- Super elements are groups of elements which are used to represent different substructures domain.
- Nine node shell element has been used to represent the superstructure-foundation. This element is multi-layer in nature to simulate the R/C structures.
- Coupled finite and infinite elements were used to model the near and far field in the soil media. These elements were employed when the modelling of soil structure interaction is in mind.

All the above elements have been formulated based on continuum mechanics principle.

(b) Constitutive modelling

The following constitutive law for different materials are used in the problem of shear wall building-foundation-soil system.

- Concrete; nonlinearities arising due to crushing, cracking and plastic yielding of concrete in one or two directions have been considered.
- Steel; the steel reinforcement is assumed to be in a uni-axial stress state and is modelled as a bilinear material with strain hardening
- Soil; to account for the nonlinear behaviour of the soil media, the nonlinear elastic model has been used

Based on the above physical and material modelling two finite element codes have been developed during the course of this study:

(i) Two dimensional finite element analysis of shear wall (2DASW)

The modified optimal triangle element, super element, interface element and the nonlinear elastic model with different numerical techniques are included in its elements technology library in this FE code.

(ii) Three dimensional finite element analysis of shear wall (3DASW)

The 3DASW finite element codes deals with constitutive nonlinearities due to concrete and steel. The multilayer shell and beam elements are available in the element library of this finite element program.

Both above finite element codes are equipped with pre, post processing and animation graphic facilities. The codes have been written using FORTRAN language and they are working under FORTRAN-95 Power Station.

Accuracy and efficiency of the finite element codes has been achieved by analysing several benchmark examples available in literature. The finite element discretisation of different numerical examples used for the verification purpose and also computational efficiency indicate that, the finite element mesh with coarse mesh and wide range of element aspect ratio using MOPT produced good results. The results show accuracy and fast rate-convergence of super element and MOPT.

An attempt has been made to highlight the computational efficiency of the developed 2DASW finite element codes by analysing actual shear wall buildings i.e. with and without opening. Results in terms of displacements and stresses are compared with those of commercial packages such as SAP-2000 and STAAD-PRO. It was observed that the contour of stress distribution, calculated by STAAD-PRO, SAP 2000 and the present study show that FE code using the present MOPT element is comparable in predicting stress distribution in the shear wall, but the MOPT element display more precise stress at the connecting beams.

Moreover, the stress distribution evaluated by the developed FE code based on MOPT element formulation with coarse FE mesh, agrees well with the stress distributions given by the commercial packages where fine mesh was used. This comparison further proves the computational efficiency of the proposed formulation of the MOPT element.

The validation of the 3DASW finite element has been made by analyzing a series of reinforced concrete (RC) structures studied by earlier researchers experimentally or analytically. The response of the RC structures in terms load–deflection curve, cracking pattern and prediction of ultimate load have been compared. It was found that the results predicted by 3DASW compared reasonably well with those reported in the literature.

An extensive study has been carried out with respect to two dimensional analysis of shear wall-foundation-soil system subjected to vertical and lateral loading. It was observed that the displacement predicted by both linear and nonlinear interactive analyses showed remarkable differences in the values of displacement and stress distribution in the shear wall. This can be attributed to stress dependant nature of the tangent modulus. The computed displacement and stresses in nonlinear interactive analysis are further increased when compared to the linear interactive analyses. The effect of the shear wall building –foundation –soil interaction cannot be overlooked.

The application of the 3DASW has been further enhanced by carrying out the inelastic analysis of the shear wall building. It was observed that;

(i) Cracking patterns were initiated at the tension side at base of the wall and then spread across width and height of the wall.

(ii) The cracking of concrete has significant influence on redistribution of normal stress σ_y. That is narrowing the zone of compression stress and transfer higher stress to un-cracked zone and reinforcement bars.

(iii) Predefined target displacement is very helpful in proper prediction of load deflection curves.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN KOD UNSUR TERHINGGA UNTUK BANGUNAN DINDING RICIH

Oleh

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2008

Pengerusi: Profesor Jamaloddin Noorzaei, PhD

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Dinding ricih biasanya digunakan sebagai anggota penting untuk menahan muatan sisi akibat beban angin atau gempa bumi. Model matematik yang jitu melibatkan struktur dinding ricih diperlukan bagi mengambil kira kesan ke atas semua komponen di dalam sistem iaitu dinding ricih, asas dan tanah. Selain daripada memerlukan model sistem yang jitu, model itu juga mestilah cekap untuk menggambarkan tindak balas struktur sistem binaan bangunan dinding ricih-asas-tanah dan ianya mestilah cekap dalam pengiraan. Tambahan lagi, memandangkan dinding ricih adalah anggota kekunci dalam susunan rangka binaan di mana ia memainkan peranan penting untuk memastikan kestabilan sistem dinding ricih di bawah muatan sisi, pertimbangan ke atas tindakbalas tidak kenyal anggota ini dalam sistem bangunan ricih adalah sangat penting.

Dengan kemajuan yang besar dalam teknologi perkomputeran, beberapa perisian unsur terhingga adalah boleh didapati secara komersial untuk penyelidik dan jurutera. Walau bagaimanapun, ini tidak menepati objektif penyelidikan ini. Dalam penyelidikan ini unsur baru telah dimajukan, perturan juzuk yang diubah suai telah dicadangkan, pengiraan algorithmik yang baru telah pun digunakan. Tambahan lagi, penyiasatan ini menumpukan kepada peningkatan keberkesanan dan model pengukuhan bangunan dinding ricih konkrit yang sesuai. Model ini meliputi model fizikal dan juzuk bahan.

(c) Model fizikal

Kebanyakan elemen yang sesuai telah pun diadaptasi dan beberapa unsur baru telah dimajukan untuk model fizikal sistem struktur dinding ricih. Unsur yang digunakan untuk tujuan pendiskretan sistem struktur dinding ricih adalah:

- Unsur modified optimal triangle (MOPT) dengan darjah kebebasan penggerudian untuk mewakili asas dan superstruktur. Unsur ini dibangunkan dalam kajian ini.
- Unsur antara muka untuk menggambarkan sifat perantaraan di antara asas yang diwakilkan oleh elemen MOPT dengan tiga darjah kebebasan di setiap nod (juzuk atas) dan media tanah (juzuk bawah) dianggap sebagai masalah tekanan satah / tegangan satah dengan dua darjah kebebasan di setiap nod. Unsur ini dimajukan untuk menggabungkan kemasukan dan pemisahan pada interface.
- Unsur super adalah kumpulan unsur yang digunakan untuk menggambarkan domain sub-struktur yang berbeza.
- Sembilan nod unsur kelompang telah digunakan untuk menggambarkan asas-superstruktur. Unsur ini adalah berbagai lapis secara semulajadi untuk simulasi struktur konkrit.

- Pasangan unsur terhingga dan takterhingga digunakan untuk menggambarkan media tanah yang dekat dan jauh, masing-masing. Unsur ini digunakan apabila model interaksi struktur-tanah perlu diambil kira.

Semua unsur di atas telah dirumus berdasarkan kepada prinsip mekanik juzuk.

(d) Model juzuk

Undang-undang juzuk untuk bahan-bahan berbeza yang terlibat dalam masalah sistem dinding ricih-asas-tanah adalah:

- Konkrit; ketidakselanjaran yang timbul akibat daripada kehancuran, keretakan dan penghasilan plastik pada konkrit dalam satu atau dua arah telah pun dipertimbangkan.
- Keluli; kekukuhan keluli dianggap berada dalam tahap tegasan satu paksi dan dimodelkan sebagai bahan dwilelurus dengan penguatan terikan.
- Tanah; bagi menerangkan sifat tak lelurus media tanah, model kenyal tak lelurus telah digunakan.

Berdasarkan kepada model fizikal dan bahan di atas, dua kod unsure terhingga telah dibangunkan menerusi kajian ini:

(iii) Analisis Dua Dimensi Struktur Dinding Ricih (2DASW)

Unsur MOPT, unsur super, unsur antara muka dan model kenyal tak lelurus dengan belbagai kaedah pengiraan telah dimasukkan dalam kod ini.

(iv) Analisis Tiga Dimensi Unsur Terhingga Struktu Dinding Ricih (3DASW)

Kod komputer 3DASW unsur terhingga ini berhubung dengan ketidakselanjaran juzuk disebabkan oleh konkrit dan keluli. Unsur belbagai lapis untuk rasuk dan kelompang boleh didapati dalam koleksi pengaturcaraan komputer unsur terhingga ini.

Kedua-dua kod unsur terhingga di atas dilengkapi dengan kemudahan pra-proses, pos-proses dan animasi grafik. Kod-kod tersebut telah dibangunkan dengan menggunakan bahasa FORTRAN dan berfungsi di bawah Stesen Kuasa FORTRAN-95.

Kecekapan dan kejituan kod unsur terhingga telah dicapai menerusi analisis beberapa contoh tanda aras yang boleh didapati dalam penerbitan. Pendiskretan unsur terhingga telah menggunakan beberapa conton sebagai tujuan verifikasi. Kecekapan pengiraan juga menunjukkan jejaring unsur terhingga dengan jaringan kasar dan belbagai aspek nisbah unsur MOPT menghasilkan keputusan yang baik. Keputusan tersebut menunjukkan ketepatan dan kepantasan kadar pertemuan elemen super dan MOPT.

Usaha telah pun dilakukan bagi menekankan kecekapan perhitungan kod unsur terhingga 2DASW yang dimajukan dengan menganalisis bangunan dinding ricih yang sebenar iaitu dengan dan tanpa bukaan. Perbandingan hasil analisis antara pakej komersial seperti SAP-2000 dan STAAD-PRO dan kod yang dibangunkan melalui kajian ini telah dibuat. Kontur agihan tegasan, yang dikira melalui STAAD-PRO, SAP 2000 dan hasil kajian ini yang menggunakan elemen MOPT menunjukkan hasil yang setanding, tapi unsur MOPT menunjukkan tegasan yang lebih tepat pada rasuk penyambung.

Lagipun, pembahagian tegasan yang ditaksir melalui kod unsur terhingga yang dibangunkan berdasarkan kepada rumusan unsr MOPT dengan jaringan kasar, sangat bersetuju dengan agihan tegasan yang diberikan oleh pakej komersial di mana jaringan yang baik digunakan. Perbandingan ini juga membuktikan ketepatan perhitungan rumusan yang dicadangkan untuk elemen MOPT.

Pengesahan elemen 3DASW unsur telah dibuat dengan menganalisis satu siri struktur konkrit yang dikaji secara eksperimen atau analisis oleh pengkaji terdahulu. Tindakbalas struktur konkrit menerusi lengkungan muatan-pembiasan, pola retakan dan ramalan muatan terbaik telah dibuat perbandingan. Hasil menunjukkan bahawa keputusan yang diramal oleh 3DASW agak bertepatan dengan apa yang telah dilaporkan sebelum ini.

Kajian yang meluas telah dijalankan berkenaan analisis dimensi sistem dinding ricih-asas-tanah yang dikenakan dengan beban menegak atau mendatar. Didapati bahawa sesaran yang diramal oleh kedua-dua analisis interaktif lelulurus dan tak lelulurus menunjukkan perbezaan ketara pada nilai sesaran dan agihan tegasan pada dinding ricih. Ini mungkin disebabkan keadaan modulus tangen yang bergantung kepada tegasan. Sesaran dan tegasan dari analisis interaktif tak selanjar didapati semakin meningkat apabila dibandingkan dengan analisis interaktif lelurus. Kesan ke atas interaksi dinding ricih-asas-tanah tidak boleh abaikan.

Aplikasi 3DSWA semakin ditingkatkan dengan melakukan analisis tak kenyal pada bangunan dinding ricih. Didapati bahawa;

(i) Corak retakan bermula pada sudut tegangan di dasar dinding tersebut dan kemudian tersebar ke seluruh lebaran dan ketinggian dinding itu.

(ii) Retakan konkrit mempunyai pengaruh penting kepada penyebaran semula tegasan normal σ_y. Ini menghadkan zon tegasan mampatan dan memindahkan tegasan yang tinggi ke zon tak retak dan tetulang.

(iii) Penentuan awal sasaran sesaran sangat membantu dalam meramalkan lengkung sesaran-beban yang sempurna.

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I certify that an Examination Committee has met on 24th April 2008 to conduct the final examination of **Masoud Paknahad** on his **Doctor of Philosophy** thesis entitled "Development of Finite Element Codes for Shear Wall Analysis" in accordance with University Pertanian Malaysia (Higher Degree) Act 1980 and University Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis was submitted to the Senate of University Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date: 14 August 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

MASOUD PAKNAHAD

Date: 10 August 2008

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