

36th Conference on

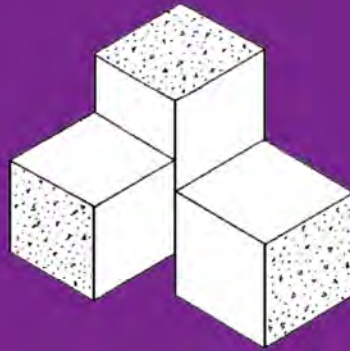
OUR WORLD IN CONCRETE & STRUCTURES

14 – 16 August 2011, Singapore

Conference Theme:

“Recent Advances in the Technology of Fresh Concrete”

Conference Documentation
Volume XXX



Conference Co-sponsors:

- BASF South East Asia Pte Ltd (*gold*)
- WAK Technologies Pte Ltd (*gold*)
- Unibeton Ready Mix, UAE
- Novaars International Pte Ltd
- Ready-Mixed Concrete Assn of Singapore
- Cement and Concrete Assn of Singapore
- Japan Concrete Institute

Organisers:

- CI-Premier Conference Organisation, Singapore

36th Conference on Our World in Concrete & Structures

OWICS 2011 Conference Advisors

- | | |
|---|---|
| <ul style="list-style-type: none">• Mr David Ball, UK• Dr O Wallevik, Iceland• Prof V Ramakrishnan, USA• Dr C C Chang, USA• Prof M C Tandon, India• Mr R Sundaram, India | <ul style="list-style-type: none">• Prof K Carter, USA• Prof Issam Harik, USA• Prof H Wallbaum, Switzerland• Prof Mario Collepardi, Italy• Mr Michael Khrapko, New Zealand• Mr Chung-Ming Ho, Taiwan |
|---|---|

OWICS 2011 Conference Committee

Conference Chairpersons:	A/Prof K C Gary Ong, NUS, Singapore A/Prof Min-Hong Zhang, NUS, Singapore
Co-ordinator:	Mr Yogesh Chhabra, Novaars International Pte Ltd
Conference Director:	Er John S Y Tan, CI-Premier Conference Organisation
Secretary:	Ms Peggy L P Teo, CONLOG
IT Manager:	Ms Amanda Quek, Singapore

The OWICS Steering Council

OWICS Honorary Emeritus Chairmen

- | | |
|------------------------------|-------------------------|
| ▪ Em Prof S L Lee, Singapore | ▪ Dr C T Tam, Singapore |
|------------------------------|-------------------------|

OWICS Honorary Chairmen

- | | |
|---------------------------|------------------------------|
| ▪ Prof Franco Mola, Italy | ▪ Mr C R Alimchandani, India |
| ▪ Prof G M Sabnis, USA | ▪ Mr Chris Stanley, UAE |
| ▪ Prof Shoji Ikeda, Japan | ▪ Prof N Otsuki, Japan |

OWICS Advisors

- | | |
|-----------------------------|----------------------------------|
| ▪ Yukio Aoyagi, Japan | ▪ Teng-Hooi Tan, Singapore |
| ▪ Ken Day, Australia | ▪ Petr Prochazka, Czech Republic |
| ▪ Willie Kay, Singapore | ▪ JiaBiao Jiang, Singapore |
| ▪ Robert G Lee, USA | ▪ Desmond King, UK |
| ▪ Hoe-Peng Lim, Singapore | ▪ Ryoji Sakurada, Japan |
| ▪ Steven Loh, Singapore | ▪ Gary K C Ong, Singapore |
| ▪ Kiat-Huat Seow, Singapore | |

OWICS Corporate Advisors

- | | |
|-------------------------------|--------------------------------|
| ▪ W R Grace Singapore Pte Ltd | ▪ BASF South East Asia Pte Ltd |
|-------------------------------|--------------------------------|

OWICS Organisation Advisors

- Ready-Mixed Concrete Association of Singapore
- American Concrete Institute-Singapore Chapter
- Singapore Concrete Institute
- Prestressed & Precast Concrete Society
- Cement and Concrete Association of Singapore
- Japan Concrete Institute
- Indian Concrete Institute

Proceedings of the 36th Conference on
OUR WORLD IN CONCRETE & STRUCTURES
14- 16 August 2011, Singapore

Theme: “Recent Advances in the Technology of Fresh Concrete”

VOLUME XXX (2011): ISBN: 978-981-08-9528-0

Editors

Dr C T Tam (OWICS)
Prof. K C G Ong (NUS)
Dr S Teng (NTU)
Prof. M H Zhang (NUS)

Conference Co-sponsors:

- BASF South East Asia Pte Ltd (*gold*)
- WAK Technologies Pte Ltd (*gold*)
- Unibeton Ready Mix, UAE
- Novaars International Pte Ltd
- Ready-Mixed Concrete Assn of Singapore
- Cement and Concrete Assn of Singapore
- Japan Concrete Institute

Organisers:

- CI-Premier Conference Organisation, Singapore

Conference Secretariat

CI-PREMIER PTE LTD

150 Orchard Road #07-14, Orchard Plaza

Singapore 238841

Tel: +65 67332922 Fax: +65 62353530

E-mail: ci-p@cipremier.com

Web: <http://www.cipremier.com>

Copyright

Not to be reprinted without written authority

The Organising Committee is not responsible for the statements made or for the opinions expressed in this Proceedings. Papers included in this proceedings are peer reviewed.

FOREWORD

The 36th Conference on Our World in Concrete and Structures (OWICS11) is themed “Recent Advances in the Technology of Fresh Concrete”. This has always been a major area of focus in this series of conference. Over the years many papers have been presented in this area of concrete research. The intention this year is to bring together all those who share a common interest in this subject area to promote the sharing of new ideas and to sharpen the focus on the significant development and innovation that has taken place in recent years.

OWICS11 is also very special as we are dedicating it to Professor Olafur H Wallervick of the Innovation Centre Iceland for his support of this conference series and for his acknowledged contributions to concrete technology. He will deliver the OWICS11 Conference lecture.

The number of eminent and world renown speakers we have this year have exceeded all our expectations and I would like to thank all speakers, authors and participants for their contributions. Thanks are also due to the OWICS Honorary Chairmen, the OWICS Advisors, our Sponsors and the Organizing Committee.

Khim Chye Gary ONG
&
Min-Hong ZHANG
Conference Chairpersons

36th Conference on Our World in Concrete & Structures 14 – 16 August 2011, Singapore

Volume XXX (2011): ISBN: 978-981-08-9528-0

Table of Contents

Foreword	iii
OWICS 2011 Dedication to Prof O H Wallevik	v
Conference Co-sponsors	xv
OWICS – Brief Milestone	xix
OWICS – Conference Awards 2010	xxix
Table of Contents	xxxiii
<i>Conference (Dedication) Lecture 2011</i>	
Rheology – My Way of Life	1
<i>Special Papers Session in honour of Prof. O H Wallevik</i>	
Theme: Chemical and mineral admixture for more sustainable structure	
High performance concrete (HPC) (revisited in 2011) P.-C. Aïtcin	13
Water on the molecular scale: solvation and the hydrated torsions method [abstract only] K.F. Alexandersson and D.C. Clary	27
The structural behaviour of SCC at rest P.H. Billberg	29
Enhancing durability and sustainability of concrete structures Yogesh Chhabra	37
Effect of limestone filler as mineral addition in self-compacting concrete G. De Schutter	49
Ecological concrete and workability: a marriage with future? S.A.A.M. Fennis and J.C. Walraven	55
Longterm creep of concrete made with porous basaltic aggregate [abstract only] J.G. Gudmundsson, G. Jónsson, O.H. Wallevik, H. Jónsson and K. Khayat	65
Eco-crete with flaky aggregates [abstract only] Hreinn Jonsson, Richard Morton and O.H. Wallevik	69
Calcined marl and clay as mineral addition for more sustainable concrete structures H. Justnes, T. Østnor, K. De Weerd and H. Vikan	73
The development of microstructure of portland cement mortars – from the fresh to the hardened state Knut O. Kjellsen and Sidney Diamond	83

Special Papers Session in honour of Prof. O H Wallevik

Chloride penetration and rheological measurements of high performance concrete [abstract only] T. I. Kristjansson and O.H. Wallevik	91
On assessment of the influence of mineral additions on early age cracking of concrete [abstract only] T.A Martius-Hammer	95
Particle packing by gyratory intensive compaction as tool to optimize the aggregate gradation of low binder scc, eco-scc [abstract only] Florian V. Mueller and Olafur H. Wallevik	97
Application of nanotechnology in concrete [abstract only] Surendra P. Shah	101
The particle flow interaction theory – thixotropic behavior and structural breakdown J. E. Wallevik	103
Alkali activated volcanic ash: steps towards a alkali activated self compacting concrete [abstract only] S.O. Wallevik, K.F. Alexandersson, J.G. Guðmundsson, T.I. Kristjánsson and O.H. Wallevik	109
Concrete incorporating supplementary cementing materials: effect of curing on compressive strength and resistance to chloride-ion penetration [abstract only] Min-Hong Zhang, Alain Bilodeau, V. Mohan Malhotra, Kwang-Soo Kim, and Jin Choon Kim	111

OWICS Steering Council Keynote Papers

Eugène Freyssinet - his incredible journey to invent and revolutionize prestressed concrete construction Authors: Pierre Xercavins, Daniel Demarthe and Ken Shushkewich, <i>presented by C.R. Alimchandani</i>	113
The disaster due to the March Eleven 2011 East Japan earthquake and tsunami [abstract only] Shoji Ikeda, Akira Hosoda and Kazuhiko Hayashi	129
Possibility of sea water as mixing water in concrete Nobuaki Otsuki, Daisuke Furuya, Tsuyoshi Saito and Yutaka Tadokoro	131
The use and abuse of the slump test for measuring the workability of concrete Christopher Stanley	139
Shape optimization of fibers in fiber reinforced concrete Petr Prochazka and Martin Valek	149

OW11 Keynote Papers

Present and future potentials in concrete engineering G. L. Balázs	165
Highly sustainable, high durability concrete for the 21st century David M J Ball	179
Damaged concrete structures by East Japan natural disaster K. Maruyama	185

Technical Papers

Study on compressive strength of concrete using low quality recycled coarse aggregate Y. Akiyoshi, Y. Sato, T. Otani, K Ueda, N. Ito and H. Okada	187
Effects of solution concentration and spray amount on the results of silver nitrate solution spray method Yusuke Aoki, Keiji Shimano and Kazuya Satoh	197
Formwork – a concrete quality tool Chirag K. Baxi	205
Self-compacting alkali activated concrete for production of concrete elements Vlastimil Bilek	215
Analytical study on high strength concrete shear walls Jimmy Chandra, Yu Liu#, and Susanto Teng	221
Survey on the mechanical properties of SCC: 20 years of research P. Desnerck, P. Van Itterbeeck , V. Boel , B. Craeye and G. De Schutter	231
Strengthening of reinforced concrete beams under torsion using CFRP sheets El Mostafa Higazy and Mahmoud El-Kateb	241
Preliminary design of high-rise shear wall with outriggers and basement fin walls on non-rigid foundation J.C.D. Hoenderkamp	249
Evaluation of shrinkage cracking resistance for concrete containing mineral admixture by embeded reinforcing bar test H.Y. Jiang, T. Otani , Y. Sato , K. Ueda , T. Mishima and A. Oshiro	259
Synthesis and properties of high calcium fly ash based geopolymer for concrete applications P. Kamhangrittirong, P. Suwanvitaya , P. Suwanvitaya and P. Chindapasirt	269
Assessment of strength, permeability and hydraulic diffusivity of concrete through mercury intrusion porosimetry B. Kondraivendhan, B. Sabet Divsholi and Susanto Teng	277
Chloride penetration profiles in existing harbor structures constructed with blast furnace cement concrete M. Kubota, T. Saito , N. Otsuki and M. Miura	287
Effect of ultra fine slag replacement on durability and mechanical properties of high strength concrete Darren T.Y. Lim; Da Xu; B. Sabet Divsholi; B. Kondraivendhan and Susanto Teng	293
Evaluation of high performance concrete using electrical resistivity technique Darren T.Y. Lim, B. Sabet Divsholi, Da Xu and Susanto Teng	303
Shear analysis of reinforced concrete slabs with effective moment of inertia Yu Liu, Jimmy Chandra and Susanto Teng	313
Performance of rehabilitated rc beam-column sub-assembly under cyclic loading C. Marthong, S.K. Deb and A. Dutta	323

Technical Papers

Development of monitoring system for corrosion protect effect after patch repair Kenyu Muratani, Suguru Takeuchi, Shinichi Miyazato, Kosuke Yokozeki and Toshinori Oyamoto	333
Impact of high temperature on different combinations of fiber reinforced concrete S. Peskova and P.P. Prochazka	339
Behaviour of high strength metakaolin concrete at elevated temperatures N.V. Ramana Rao, Z. Abdul Rahim, P. Srinivasa Rao and T. Seshadri Sekhar	349
Durability of reinforced fly ash-based geopolymer concrete in the marine environment D.V. Reddy, J-B Edouard, K. Sobhan and S.S. Rajpathak	355
Effect of doping position of Sr Atom on crystal stability of beta-form belite R. Sakurada, A. K. Singh and Y. Kawazoe	365
Development on specific evaluation technique for the prediction of neutralization of concrete S. Sato, Y. Masuma, Y. Hasegawa, I. Natsuka, S. Aoyama and K. Yokoi	373
Influence of excessive bleeding on frost susceptibility of concrete incorporating ferronickel slag as aggregates Takayasu Sato, Kohei Watanabe, Akihiro Ota, Minoru Aba and Yuki Sako	381
The Asian experience in low fines self consolidating concrete (scc) in everyday applications Seow Kiat Huat, Nilotpol Kar, Dr Feng Qiuling	389
Creep deformations on high strength concrete made of montmorillonite mineral nano particles A.Sprince, L. Pakrastinsh and A. Korjakins	397
Some studies on flexural behaviour of glass fibre reinforced concrete members P. Sravana, P.Srinivasa Rao, K. Chandramouli, T. Seshadri Sekhar and P. Sarika	407
Studies on thermal cycles of glass fibre concrete mixes P. Srinivasa Rao, Mouli Chandra, T. Seshadri Sekhar, N. Pannirselvam P.Sravana and P. Sarika	413
Influence of fine-grained fraction amount in recycled fine aggregate on properties of mortar Shingo Tabata, Shinichi Miyazato, Takashi Habuchi, Takahiko Amino and Hidechika Tanaka	419
Sulfuric acid resistance of autoclaved cementitious materials containing γ -CaO·SiO and quartz Yuriko Tsuburaya, Nobuaki Otsuki, Tsuyoshi Saito and Saphouvong Khamhou	425
Performance evaluation of mortar mixed with fly ash - blast furnace slag and estimate of its environmental impact Masayuki Watanabe and Shinichi Miyazato	433
Mechanical properties and durability of high performance concrete incorporating ultra fine slag and undensified silica fume Da Xu, B. Sabet Divsholi, Darren T.Y. Lim and Susanto Teng	441

A Chapter on The Conceptual Approach to Structural Design

Keynote Papers

Recent developments in the conceptual design of r.c. and p.c. structures F. Mola, E. Mola and L.M. Pellegrini	451
Seismic sustainability of a contemporary architectural expression M. Mezzi, F. Comodini and F. Marinacci	467
Innovative retrofit for upgrading reinforced concrete decks on non-composite steel girder bridges A.Peiris and I. Harik	477
Tall building design inspired by nature Mark Sarkisian	485

Technical Papers

Assessment and statically loading of haraz r.c frame type arch bridge M.H.A. Beygi, R. Moradi, A. R. Azizian, N. Ranjbar and H. R. H. A. Beygi	495
Ultra high performance and high early strength concrete Mehdi Sadeghi e Habashi	503
Study of fracture energy properties of portland blast furnace cement type-b concrete with partial replacement of aggregate with porous ceramic course aggregate M.M. Macharia, R. Sato, A. Shigematsu and H. Onishi	509
Architecture towards seismic engineering M. Mezzi and A. Parducci	517
Study of the hybrid structures changed from the steel bridges for railroad which considered construction Nozomu Taniguchi, Masanori Hansaka, Norio Koide, Kazuo Ohgaki, Fujikazu Okubo and Toshiyuki Saeki	525
Index of Authors	xxxix

INDEX OF AUTHORS

Author	Pg No.	Author	Pg No.
Aba, Minoru	381	Habuchi, Takashi	419
Abdul Rahim, Z.	349	Hansaka, Masanori	525
Aïtcin, P.-C.	13	Harik, I.	477
Akiyoshi, Y.	187	Hasegawa, Y.	373
Alexandersson, K.F.	27, 109	Hayashi, Kazuhiko	129
Alimchandani, C.R.	113	Higazy, El Mostafa	241
Amino, Takahiko	419	Hoenderkamp, J.C.D.	249
Aoki, Yusuke	197	Hosoda, Akira	129
Aoyama, S.	373	Ikeda, Shoji	129
Azizian, A.R.	495	Ito, N.	187
Balázs, G.L.	165	Jiang, H.Y.	259
Ball, David M.J.	179	Jónsson, G	65
Baxi, Chirag K.	205	Jónsson, H.	65, 69
Beygi, H. R. H. A.	495	Justnes, H.	73
Beygi, M.H.A.	495	Kamhangrittirong, P.	269
Bilek, Vlastimil	215	Kar, Nilotpol	389
Billberg, P.H.	29	Kawazoe, Y.	365
Bilodeau, Alain	111	Khamhou, Saphouvong	425
Boel, V.	231	Khayat, K.	65
Chandra, Jimmy	221, 313	Kim, Jin Choon	111
Chandramouli, K.	407, 413	Kim, Kwang-Soo	111
Chhabra, Yogesh	37	Kjellsen, Knut O.	83
Chindapasirt, P.	269	Koide, Norio	525
Clary, D.C.	27	Kondraivendhan, B.	277, 293
Comodini, F.	467	Korjaks, A.	397
Craeye, B.	231	Kristjansson, T. I.	91, 109
De Schutter, G.	49, 231	Kubota, K.	287
De Weerd, K.	73	Lim, Darren T.Y.	293, 303, 441
Deb, S.K.	323	Liu, Yu	221, 313
Demarthe, Daniel	113	Macharia, M.M.	509
Desnerck, P.	231	Malhotra, V. Mohan	111
Diamond, Sidney	83	Marinacci, F.	467
Dutta, A.	323	Marthong, C.	323
Edouard, J-B	355	Mishima, T.	259
El-Kateb, Mahmoud	241	Martius-Hammer, T.A.	95
Feng Qiuling	389	Maruyama, K.	185
Fennis, S.A.A.M.	55	Masuma, Y.	373
Furuya, Daisuke	131	Mezzi, M.	467, 517
Gudmundsson, J.G.	65, 109	Miura, M.	287
Habashi, Mehdi Sadeghi e	503	Miyazato, Shinichi	333, 419, 433

INDEX OF AUTHORS

Author	Pg No.	Author	Pg No.
Mola , E.	451	Sato. S.	373
Mola, F.	451	Satoh, Kazuya	197
Moradi, R.	495	Seow Kiat Huat	389
Morton, Richard	69	Seshadri Sekhar, T.	349, 407, 413
Mueller, Florian V.	97	Shah, S.P.	101
Muratani, Kenyu	333	Shigematsu. A.	509
N.V. Ramana Rao, N.V.	349	Shimano, Keiji	197
Natsuka, I.	373	Shushkewich, Ken	113
Ohgaki, Kazuo	525	Singh, A.K.	365
Okada, H.	187	Sobhan, K.	355
Okubo, Fujikazu	525	Sprince, A.	397
Onishi, H.	509	Sravana, P.	407, 413
Oshiro, A.	259	Srinivasa Rao, P.	349, 407, 413
Østnor, T.	73	Stanley, Christopher	139
Ota, Akihiro	381	Suwanvitaya, P.	269
Otani, T	187, 259	Tabata, Shingo	419
Otsuki, Nobuaki	131, 287, 425	Tadokoro, Yutaka	131
Oyamoto, Toshinori	333	Takeuchi, Suguru	333
Pakrastinsh, L.	397	Tanaka, Hidechika	419
Pannirselvam, N.	413	Taniguchi, Nozomu	525
Parducci, A.	517	Teng, Susanto	221, 277, 293
Peiris, A.	477		303, 313, 441
Pellegrini, L.M.	451	Tsuburaya, Yuriko	425
Peskova, S.	339	Ueda, K.	187, 259
Prochazka, Petr	149, 339	Valek, Martin	149
Rajpathak, S.S.	355	Van Itterbeeck, P.	231
Ranjbar, N.	495	Vikan, H.	73
Reddy, D.V.	355	Wallevik, J.E.	103
Sabet Divsholi, B.	277, 293, 303, 441	Wallevik, O.H.	1, 65, 69, 91
Saeki, Toshiyuki	525		97, 109
Saito, Tsuyoshi	131, 287, 425	Wallevik, S.O.	109
Sakoi, Yuki	381	Walraven, J.C.	55
Sakurada, R.	365	Watanabe, Kohei	381
Sarika, P.	407, 413	Watanabe, Masayuki	433
Sarkisian, Mark	485	Xercavins, Pierre	113
Sato, R.	509	Xu, Da	293, 303, 441
Sato, Takayasu	381	Yokoi, K.	373
Sato, Y.	187, 259	Yokozeki, Kosuke	333
		Zhang, Min-Hong	111

For Link, please click on page numberrrs

ISBN: 978-981-08-9528-0

SHEAR ANALYSIS OF REINFORCED CONCRETE SLABS WITH EFFECTIVE MOMENT OF INERTIA

Yu Liu*, Jimmy Chandra[#] and Susanto Teng[#]

*School of Civil & Environmental Engineering
Nanyang Technological University
Blk N1, #50 Nanyang Avenue, Singapore 639798
e-mail: <cliuy@ntu.edu.sg> webpage: <http://www.cee.ntu.edu.sg/>

Keywords: Reinforced concrete slabs, Finite element analysis, Shear failure, Effective stiffness

Abstract. *The effective moment of inertia concept has been used to evaluate the bending stiffnesses of reinforced concrete (RC) members in design codes. Later, it was combined with finite element (FE) methods to calculate the deflection responses of RC slabs. However, the failure of the slabs cannot be predicted by the effective moment of inertia based method. In this work, an empirical failure criterion for RC slabs under bending and shear was adopted and modified to consider the stiffness degradation of shell elements in FE analysis. In order to predict the shear failure of the slabs, a softening curve for the bending and shear stiffnesses was proposed. The model parameters in the failure criterion were calibrated according to published test results. The comparison between the numerical and the experimental results shows that the proposed method can predict the deflection response and the shear strength of the analyzed slabs with acceptable accuracy.*

1 INTRODUCTION

The finite element (FE) analysis of reinforced concrete (RC) slabs is generally carried out by adopting either a layered element approach or an effective stiffness approach¹. The layered approach divides the plate or shell elements into several layers through the thickness, and each layer has its own independent material properties. The layered plate or shell elements can be used to easily consider the nonlinear properties of concrete and the presence of steel reinforcements. Hence, their application in the FE analysis of RC slabs has been popular²⁻⁴. With the layered approach, one needs to call the constitutive model of concrete for each layer at each integration point of the elements. Hence, the analysis can be expensive and time consuming. Furthermore, the difficulties and complexities in modeling the concrete restrict the accuracy of the analysis results.

On the other hand, the effective stiffness approach⁵⁻⁶ adopts an empirical effective bending stiffness of the element cross section to replace the iteration through the thickness for summing up the contributions of each layer. This approach can provide reasonable estimates of slab deflections in the early stage of loading. The computational cost is also much lower as compared with the layered method. However, the failure of the slabs cannot be predicted by using this method.

In this work, efforts have been made to predict the shear failure of reinforced concrete (RC) slabs through FE analysis using the effective stiffness approach. In the next section, the used

[#] Nanyang Technological University, Singapore

finite element is described. Then, in Section 3, the material matrix based on the effective moment of inertial concept is derived. In order to predict the shear failure of the slabs, a softening curve for the bending and shear stiffnesses is also proposed based on an empirical failure criterion for RC slabs under bending and shear. Some numerical examples are worked out and compared with the experimental results in Section 4 and the paper is summarized in Section 5.

2 FINITE ELEMENT FORMULA

In this work, a 9-node heterosis shell element⁷ is adopted. It had been modified to be a non-layered form⁸. In the non-layered shell element, the general strain vectors comprises of 8 component, i.e.,

$$\boldsymbol{\varepsilon} = \{\varepsilon_{0x} \quad \varepsilon_{0y} \quad \gamma_{0xy} \quad \gamma_{xz} \quad \gamma_{yz} \quad \varphi_x \quad \varphi_y \quad \varphi_{xy}\}^T \quad (1)$$

where ε_{0x} , ε_{0y} and γ_{0xy} are the in-plane strains at mid-plane ($z = 0$); γ_{xz} and γ_{yz} are the transverse shear strains; φ_x , φ_y and φ_{xy} are the curvatures. The new 8×45 geometric matrix which maps the general nodal displacements into the general strains, $\mathbf{B}_n$, was derived to replace the original 5×45 geometric matrices, $\mathbf{B}$, for the layered element where the general strain vectors include only 5 components (ε_x , ε_y , γ_{xy} , γ_{xz} and γ_{yz}).

The first 5 rows of $\mathbf{B}_n$ are the same as those of matrix $\mathbf{B}$ at mid-layer ($z = 0$). The last 3 rows of $\mathbf{B}_n$ are obtained from

$$\begin{Bmatrix} \varphi_x \\ \varphi_y \\ \varphi_{xy} \end{Bmatrix} = \begin{bmatrix} \partial_x & 0 \\ 0 & \partial_y \\ \partial_y & \partial_x \end{bmatrix} \cdot \begin{Bmatrix} \theta_x \\ \theta_y \end{Bmatrix} = \sum_{i=1}^9 \begin{bmatrix} N_x^i & 0 \\ 0 & N_y^i \\ N_y^i & N_x^i \end{bmatrix} \cdot \begin{Bmatrix} \theta_x^i \\ \theta_y^i \end{Bmatrix} \quad (2)$$

where θ_x^i and θ_y^i ($i = 1 \dots 9$) are the nodal rotation angles; N_x^i and N_y^i ($i = 1 \dots 9$) are the partial derivatives of the shape functions N^i with respect to x and y , respectively. With material matrix, $\mathbf{D}$, and the geometric matrix, $\mathbf{B}_n$, the element stiffness matrix can be obtained by numerical integration as

$$\mathbf{K}_e = \iint_{\Omega} \mathbf{B}_n^T \cdot \mathbf{D} \cdot \mathbf{B}_n \cdot d\Omega \quad (3)$$

The selective integration scheme is adopted in Eq.(3) to avoid the locking problem. The material matrix $\mathbf{D}$ is discussed in the next section.

3 MATERIAL MATRIX

3.1 Material matrix before cracking

For an orthotropic elastic plane stress problem, the stress-strain relationship is

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{1}{1-\nu_x\nu_y} \begin{bmatrix} E_x & \nu_y E_x & 0 \\ \nu_x E_y & E_y & 0 \\ 0 & 0 & (1-\nu_x\nu_y)G_{xy} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (4)$$

where E_x , ν_x and E_y , ν_y are the moduli and Poisson's ratios in x and y directions, respectively; G_{xy} is the shear modulus in x - y plane. In the shell element, the in-plane strains can be calculated from the curvatures and the mid-plane strains as

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_{0x} \\ \varepsilon_{0y} \\ \gamma_{0xy} \end{Bmatrix} + \begin{Bmatrix} \varphi_x \\ \varphi_y \\ \varphi_{xy} \end{Bmatrix} z. \quad (5)$$

The in-plane forces are thus calculated as

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} dz = \frac{t}{1-\nu_x\nu_y} \begin{bmatrix} E_x & \nu_y E_x & 0 \\ \nu_x E_y & E_y & 0 \\ 0 & 0 & (1-\nu_x\nu_y)G_{xy} \end{bmatrix} \begin{Bmatrix} \varepsilon_{0x} \\ \varepsilon_{0y} \\ \gamma_{0xy} \end{Bmatrix} \quad (6)$$

where t is the thickness. The moments are obtained as

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} z dz = \frac{t^3/12}{1-\nu_x\nu_y} \begin{bmatrix} E_x & \nu_y E_x & 0 \\ \nu_x E_y & E_y & 0 \\ 0 & 0 & (1-\nu_x\nu_y)G_{xy} \end{bmatrix} \begin{Bmatrix} \varphi_x \\ \varphi_y \\ \varphi_{xy} \end{Bmatrix}. \quad (7)$$

The transverse shear forces-strain relationship is

$$\begin{Bmatrix} Q_x \\ Q_y \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \tau_{xz} \\ \tau_{yz} \end{Bmatrix} dz = t \begin{bmatrix} G_{xz} & 0 \\ 0 & G_{yz} \end{bmatrix} \begin{Bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} \quad (8)$$

From Eqs.(6)-(8), the material matrix $\mathbf{D}$ is obtained as

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ Q_x \\ Q_y \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{tE_x}{1-\nu_x\nu_y} & \frac{t\nu_y E_x}{1-\nu_x\nu_y} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{t\nu_x E_y}{1-\nu_x\nu_y} & \frac{tE_y}{1-\nu_x\nu_y} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & tG_{xy} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & tG_{xz} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & tG_{yz} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{E_x t^3/12}{1-\nu_x\nu_y} & \frac{\nu_y E_x t^3/12}{1-\nu_x\nu_y} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{\nu_x E_y t^3/12}{1-\nu_x\nu_y} & \frac{E_y t^3/12}{1-\nu_x\nu_y} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{t^3 G_{xy}}{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_{0x} \\ \varepsilon_{0y} \\ \gamma_{0xy} \\ \gamma_{xz} \\ \gamma_{yz} \\ \varphi_x \\ \varphi_y \\ \varphi_{xy} \end{Bmatrix} \quad (9)$$

Before cracking, the shell elements behave linearly, and

$$E_x = E_y = E_c, \quad \nu_x = \nu_y = \nu_c, \quad G_{xy} = G_{xz} = G_{yz} = G_c = \frac{E_c}{2(1+\nu_c)} \quad (10)$$

where E_c and ν_c are the modulus and the Poisson's ratio of the concrete, respectively.

3.2 Stiffness reduction factors

After cracking, the stiffnesses of the shell element, in Eq.(9), will degrade. Polak⁵ and Vecchio & Taha⁶ defined the stiffness reduction factors α_x and α_y to consider the concrete cracking induced stiffness degradation in the x - and y - directions, respectively. The stiffness reduction factors α_x and α_y were defined based on the concept of effective moment of inertia, which is calculated as,

$$I_e = \left(\frac{M_{cr}}{M^e} \right)^a I_g + \left[1 - \left(\frac{M_{cr}}{M^e} \right)^a \right] I_{cr} \quad (11)$$

where $M_{cr} = \frac{f_r I_g}{y_t}$ is the cracking moment; $f_r = 0.6\sqrt{f'_c}$ is the modulus of rupture of the concrete; y_t is the distance from neutral axis to the tension face of the uncracked section; I_g is the gross moment of inertia; I_{cr} is the moment of inertia of the fully cracked cross section; M^e is the elastic bending moment; and $a = 3$.

Given the details of the element's cross sections in x - and y - directions and the current general strain vector, the effective moment of inertias in x - and y - directions, I_{ex} and I_{ey} , can be calculated. To account for the torsional moment, M_{xy} , in the shell elements, the elastic bending moment, M^e , in Eq.(11), was suggested to be replaced by a generalized moment, $\tilde{M}^e$, as

$$\tilde{M}_x^e = |M_x^e| + |M_{xy}^e|, \quad \tilde{M}_y^e = |M_y^e| + |M_{xy}^e| \quad (12)$$

where the elastic moments M_x^e , M_y^e and M_{xy}^e are calculated from Eq.(9) when Eq.(10) is used. The stiffness reduction factors α_x and α_y were thus defined as,

$$\alpha_x = I_{ex}/I_{gx}, \quad \alpha_y = I_{ey}/I_{gy} \quad (13)$$

Finally, the concrete cracking induced stiffness degradation of the shell elements is taken into account by α_x and α_y , and Eq.(10) is updated as

$$\begin{aligned} E_x &= \alpha_x E_c, & E_y &= \alpha_y E_c, & v_x &= \alpha_x v_c, & v_y &= \alpha_y v_c \\ G_{xy} &= \alpha_x \alpha_y G_c, & G_{xz} &= \alpha_x G_c, & G_{yz} &= \alpha_y G_c \end{aligned} \quad (14)$$

It has been shown that with Eq.(14), the reasonably good estimates to the deflection of RC slabs under service load level can be achieved⁶.

3.3 Modified stiffness reduction factors

To predict the failure of the analyzed slabs, we need to account for the further degradation of the stiffnesses due to steel yielding and shear failure of the concrete. In this work, an empirical failure criterion for RC slabs subjected to shear and bending by Yamada et. al.⁹ is used, i.e.,

$$\left(\frac{M/M_n}{1.43}\right)^2 + \left(\frac{V/V_n}{1.43}\right)^2 = 1 \quad (15)$$

where M_n and V_n are the bending moment capacity and the shear capacity of the considered slab, respectively. To measure the further stiffness degradation of the shell elements, a factor R is defined, similar to Eq.(15), as

$$R = \left(\frac{M/M_n}{C_M}\right)^2 + \left(\frac{Q/Q_n}{C_Q}\right)^2 \quad (16)$$

where C_M and C_Q are model parameters which will be discussed in the next section. The bending moment capacity of the considered cross section can be calculated as

$$M_n = \rho d f_y j_d \quad (17)$$

where ρ is the tension steel reinforcement ratio; d is the effective depth of slab; f_y is the yielding strength of the tension steel; and j_d is the distance from the tension steel to the resultant compressive force of the cross section. The shear capacity is calculated using the empirical formula¹⁰, i.e.,

$$Q_n = 59t \left[f'_c (\rho + \rho') \frac{Qd}{M} \right]^{1/3} + d \rho_w f_{y1} \quad (18)$$

where ρ' is the compression steel reinforcement ratio; f'_c is the compressive strength of concrete in psi; ρ_w is the shear steel reinforcement ratio; and f_{y1} is the yielding strength of the shear steel.

During FE analysis, the factors used to measure the further stiffness degradation in x - and y -directions, R_x and R_y , can be calculated according to Eqs.(16)-(18). The modified stiffness reduction factors are then defined as

$$\alpha'_x = \alpha_x / (1 + R_x), \quad \alpha'_y = \alpha_y / (1 + R_y) \quad (19)$$

In this work, the stiffness reduction factors α_x and α_y in Eq.(14) are replaced by the modified factors α'_x and α'_y in Eq.(19). The softening caused by steel yielding and shear failure of the concrete is thus taken into account.

4 NUMERICAL EXAMPLES

The material matrix discussed above has been implemented as a user defined material in the finite element analysis program FEAP¹¹. The secant stiffness scheme is adopted in the computation. The model parameters C_M and C_Q in Eq.(16) are chosen as 3.3 and 1.6 by trial and error method. Three series of slabs are analysed and the obtained results are compared with the test results. The first and the second series include four slabs tested at Talbot laboratory, University of Illinois by Elstner and Hognestad¹². The third series includes five slabs tested at research and development laboratory of Portland Cement Association also by Elstner and Hognestad¹².

4.1 Slabs supported on four edges with corners free to lift (Series II)¹²

The series II of the experiment involved 3 panels of 152.4mm thick slabs loaded monolithically through 356mm column stubs. The slabs were simply supported at four edges with the corners free to lift. The slab details are shown in Table 1.

Specimen	Dimensions (mm)	Depth (mm)	Concrete		Reinforcement		
			f'_c (MPa)	E_c (MPa)	f_y (MPa)	ρ' %	ρ %
A-4	1828.8 × 1828.8 × 152.4	117.6	26.2	24449	332.7	0.6	1.2
A-5	1828.8 × 1828.8 × 152.4	114.3	27.8	25212	321.7	1.2	2.5
A-6	1828.8 × 1828.8 × 152.4	114.3	25.1	23947	321.7	1.2	3.7

Table 1: Details of slabs in series II

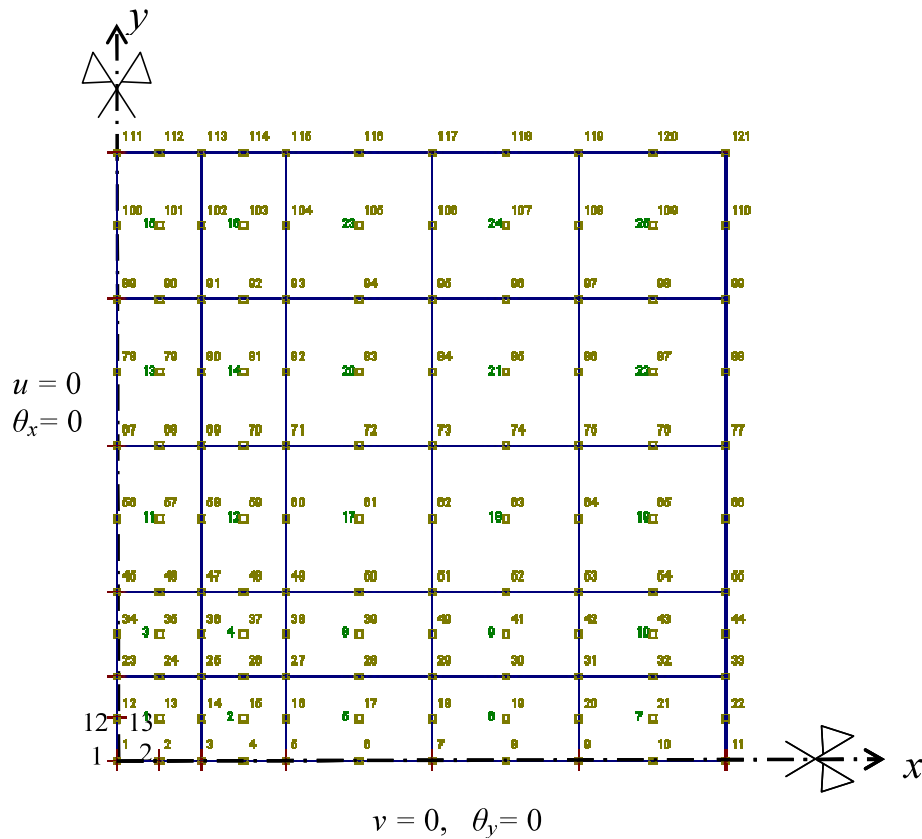


Figure 1: Computational modelling of slabs

A quarter of slab is modelled using 121 nodes and 25 elements as shown in Figure 1. The loadings were applied equally at nodes 1, 2, 12 and 13 (position of column stud). Since only a quarter of slab is modelled, the rotation angle θ_y , and the displacement v of the boundary nodes on line $y = 0$ are zeros, because of symmetry. The rotation angle θ_x , and the displacement u of the boundary nodes on line $x = 0$ are also zeros. The obtained results of load versus central deflection curves are plotted in Figure 2 together with the test results. The typical deflection distributions at the early stage and the near failure stage are shown in Figure 3. From Figure 3b, the deformation localization close to the column can be observed, which indicates that a punching shear failure has happened. The numerical results are generally agreeable with the experimental results.

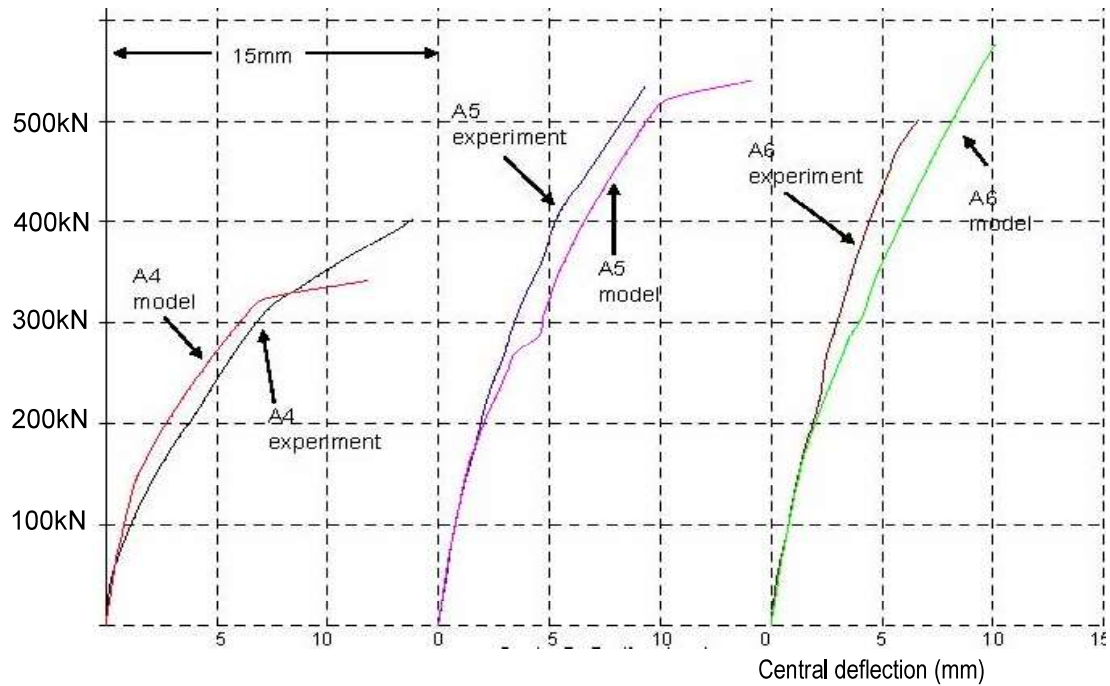
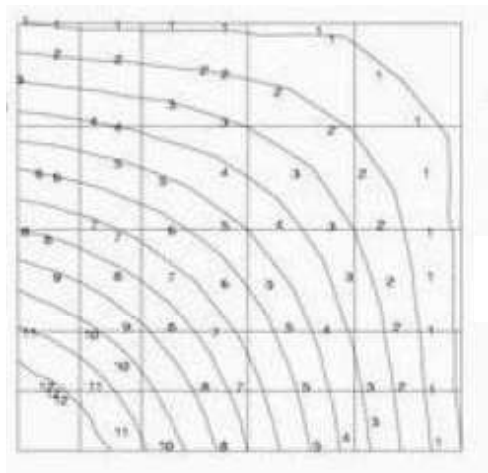
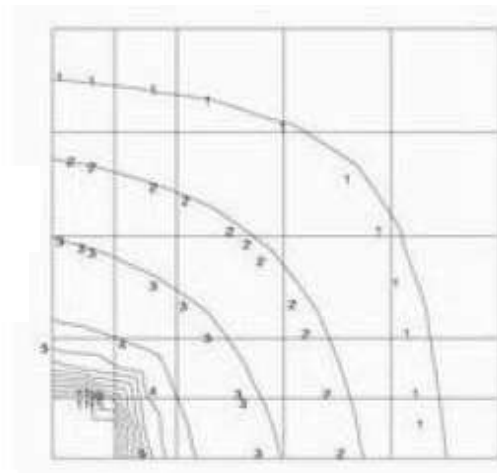


Figure 2: Load-central deflection curves of slabs in series II



a. Deflection distribution at early stage



b. Deflection distribution near failure

Figure 3: Typical deflection distributions

4.2 Slabs supported at four corners (Series IV)¹²

The series IV involves one slab supported on four corners and loaded through a 254mm column stub. The details of the slab are shown in Table 2. Similarly, a quarter of the slab is modelled with 121 nodes and 25 elements and the symmetric boundary conditions are applied to the nodes on lines $x = 0$ and $y = 0$. The obtained load versus central deflection curve are plotted and compared with the test result in Figure 4. The predicted strength conforms to the experimental result while the predicted central deflection is larger than the experimental observation.

Specimen	Dimensions (mm)	Depth (mm)	Concrete		Reinforcement		
			f'_c (MPa)	E_c (MPa)	f_y (MPa)	ρ' %	ρ %
A7a	1828.8 × 1828.8 × 152.4	114.3	28.5	25293	321.7	1.2	2.5

Table 2 Details of slab A7a in series IV

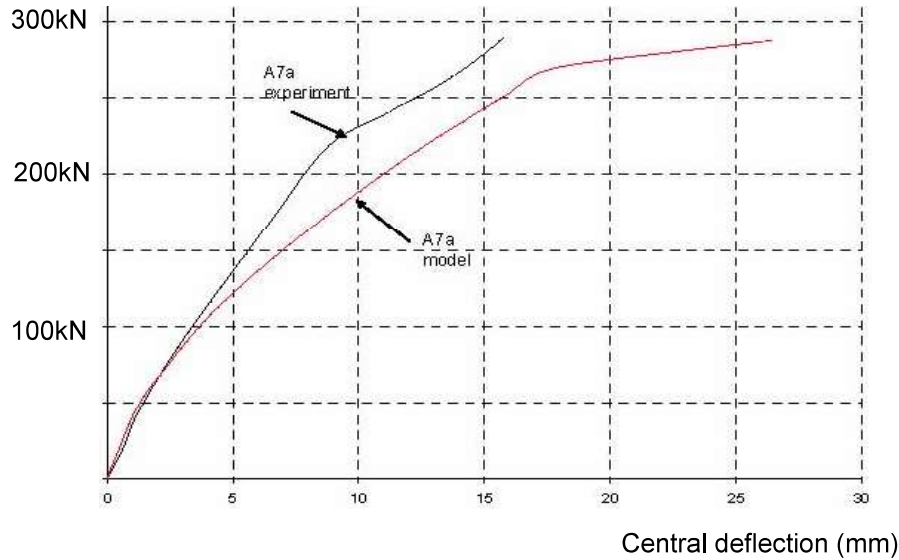


Figure 4: Load-central deflection curves for slab in series IV

4.3 Slabs supported on four edges with corners free to lift (Series VIII)¹²

In this work, 5 slabs in series VIII are also selected to analysis. They are loaded through 254mm column stubs, and simply supported at four edges with the corners free to lift. There is no compression steel and the tension steel reinforcement ratios range from 0.5% to 3.0%. For the slab DEH B12, two rows of vertical stirrup with cross sectional area of 1419mm² were used, and the shear reinforcement ratio is about 0.57%. The slab details are shown in Table 3. Again, a quarter of the slab is modelled with 121 nodes and 25 elements and the symmetric boundary conditions are applied at lines $x = 0$ and $y = 0$. The obtained load versus central deflection curves are compared with the test results in Figure 5.

Specimen	Dimensions (mm)	Depth (mm)	Concrete		Reinforcement		
			f'_c (MPa)	E_c (MPa)	$f_y = f_{y1}$ (MPa)	ρ_w %	ρ %
DEH B02	1828.8 × 1828.8 × 152.6	114.3	47.6	32978	320.6	-	0.5
DEH B04	1828.8 × 1828.8 × 152.6	114.3	47.7	33013	303.4	-	1.0
DEH B09	1828.8 × 1828.8 × 152.6	114.3	43.9	31670	341.3	-	2.0
DEH B14	1828.8 × 1828.8 × 152.6	114.3	50.5	33968	325.4	-	3.0
DEH B12	1828.8 × 1828.8 × 152.6	114.3	45.9	32384	331.6	0.57	3.0

Table 3 Details of slabs in series VIII

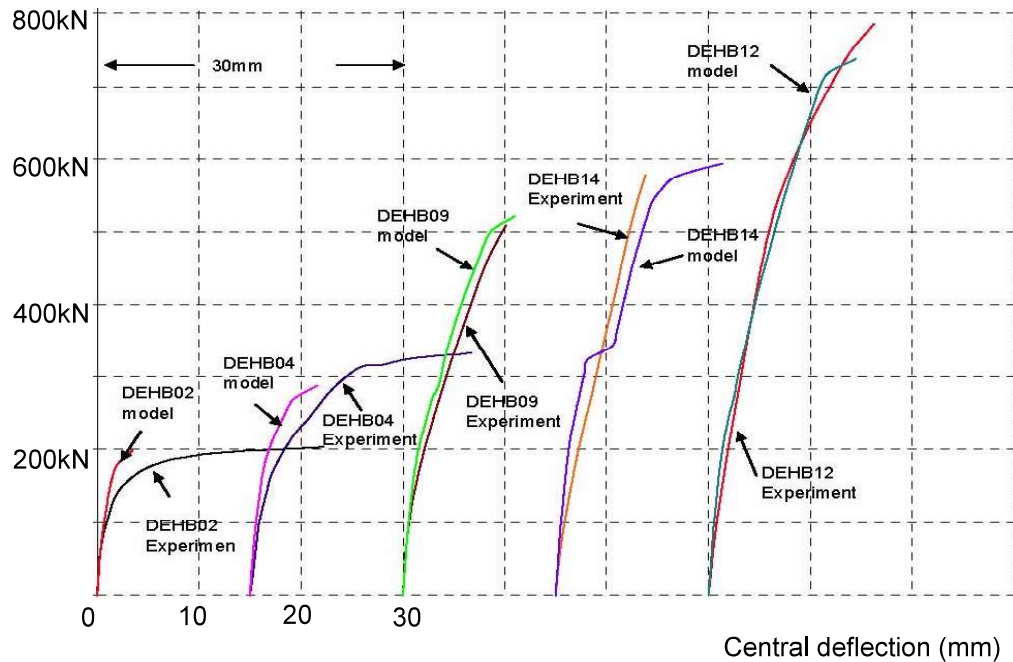


Figure 5 Load-central deflection curves for slab in series VIII

In experiment, slabs B09, B12 and B14 are observed to fail by punching shear. The predicted strengths and central deflections generally agree with the test results. For slabs B02 and B04, the numerical results still suggest a shear failure; however, they are actually failed by flexure in the experiment. It shows that, the proposed method maybe only applicable for the slabs subjected to shear failure

5 CONCLUSIONS

In this work, efforts have been made to predict the failure of RC slabs using the FE analysis based on the effective stiffness approach. The non-layered form of the 9-node heterosis shell element is used and the degradation of material matrix due to concrete cracking is reflected by the stiffness reduction factors. In order to predict the failure of the slabs, a softening curve for the bending and shear stiffnesses was proposed based on an empirical failure criterion for RC slabs under bending and shear. The stiffness reduction factors defined by Polak⁵ are modified accordingly to consider the further degradation of the stiffnesses due to steel yielding and shear failure of the concrete. The model parameters C_M and C_Q in the softening curve are set to be 3.3 and 1.6, respectively, by trial and error method. Three series of RC slabs were analysed using the proposed method. The computed deflection responses and shear strengths are agreeable with the test results for the slabs subjected to shear failure. Further work is needed to predict the deflection and the strength of slabs subjected to flexure.

REFERENCES

- [1] J. Jiang and F. A. Mirza, "Nonlinear analysis of reinforced concrete slabs by a discrete finite element approach", *Computers and Structures*, 65(4), 585-592, (1997).
- [2] H.W. Song, S.H. Shim and K.J. Byun, "Failure analysis of reinforced concrete shell structures using layered shell element with pressure node", *ASCE Journal of Structural Engineering*, 128(5), 655-664, (2002).
- [3] S. Teng, Y. Liu and C.K. Soh, "Flexural analysis of reinforced concrete slabs using degenerated shell element with assumed strain and 3-D concrete model", *ACI Structural Journal*, 102(4), 515-525, (2005).
- [4] W.Y. Wang and S. Teng, "Finite-element analysis of reinforced concrete flat plate structures by layered shell element." *ASCE Journal of Structural Engineering*, 134(12), 1862-1872, (2008).
- [5] M.A. Polak "Effective stiffness model for reinforced concrete slabs", *ASCE Journal of Structural*

Engineering, 122(9), 1025-1030, (1996).

[6] F.J. Vecchio and M. Tata, "Approximate analysis of reinforce concrete slabs", *Structural Engineering and Mechanics*, 8(1), 1-18, (1999).

[7] E. Hinton and D.R.J. Owen, *Finite Element Software for Plates and Shells*, Pineridge Press, Swansea, U.K. (1984).

[8] Y. Liu and S. Teng, "Nonlinear analysis of reinforced concrete slabs using nonlayered shell element", *ASCE Journal of Structural Engineering*, 134(7), 1092-1100, (2008).

[9] T. Yamada, A. Nanni and K. Endo, "Punching shear resistance of flat slabs: influence of reinforcement type and ratio", *ACI Structural Journal*, 88(4), 555-563, (1992).

[10] ASCE-ACI Committee 445 on Shear and Torsion, "Recent approach to shear design of structural concrete", *ASCE Journal of Structural Engineering*, 124(12), 1375-1404, (1998).

[11] R.L. Taylor *FEAP--A Finite Element Analysis Program, V7.4 programmer manual*, Univ. of California at Berkeley, (2001).

[12] R.C. Elstner and E. Hognestad, "Shearing strength of reinforced concrete slabs," *ACI Journal Proceedings*, 53(1), 29-58, (1956).

- Word Count: 2458

Plagiarism Percentage

17%

sources:

- 1 6% match (publications)
[Liu, Yu. and Susanto Teng. "Nonlinear Analysis of Reinforced Concrete Slabs Using Nonlayered Shell Element". Journal of Structural Engineering, 2008.](#)

- 2 3% match (Internet from 03-Nov-2012)
<http://www.demoforests.net/Warehouse/Docs/Other/Wensel/CACTOS/Note6.pdf>

- 3 2% match (Internet from 09-Mar-2016)
http://ir.canterbury.ac.nz/bitstream/handle/10092/6410/dann_thesis.pdf?isAllowed=y&sequence=1

- 4 2% match (Internet from 08-Feb-2014)
<http://kurskservice.ru/2011-06-19-16-54-17/63-bonus.pdf>

- 5 2% match (Internet from 02-Jul-2013)
http://svn.gna.org/svn/freeciv/tags/R1_14_1/data/misc/intro.xpm

- 6 2% match (Internet from 20-Oct-2013)
<http://www2.americanexpress.ro/Amex/pdf/ro/AMEX%2013%2002%202013.xls>

- 7 1% match (Internet from 07-Feb-2014)
<http://66.180.169.221/pdf/314.pdf>

paper text:

finite element is described. Then, in Section 3, the material matrix based on the effective moment of inertial concept is derived. In order to predict the shear failure of the slabs, a softening curve for the bending and shear stiffnesses is also proposed based on an empirical failure criterion for RC slabs under bending and shear. Some numerical examples are worked out and compared with the experimental results in Section 4 and the paper is summarized in Section 5.

2 FINITE ELEMENT FORMULA

In this work, a 9-node heterosis shell element 7 is adopted. It had been modified to be a non-layered form⁸. In the non-layered shell element, the general strain vectors comprises of 8 component, i.e., (1) where E_0 , E_0 , and Y_0 , are the in-plane strains at mid-plane ($z = 0$); Y_u and y_u are the transverse shear stains; p_u , p_v , and p_{θ} , are the curvatures. The new B_{x45} geometric matrix which maps the general nodal displacements into the general strains, B_n , was

derived to replace the original 5×45 geometric matrices, B , for the

1

layered element where the general strain vectors include only 5 components (ϵ , ϵ_x , ϵ_y , γ and γ_{xy}). The first 5 rows of B_n are the same as those of matrix B at mid-layer

($z = 0$). The last 3 rows of B_n are obtained from

1

$[mY_{<<.piz>y,,] [acl0, clo] \{00''\} = '[_{,}[NN0''! oNN;,:'] \cdot \{ : ''\} (2) = , \cdot y \times y$ where θ_i and θ_{i1} ($i = 1 \dots 9$) are the nodal rotation angles; N_i and N_{i1} ($i = 1 \dots 9$) are the partial $y \times y$

derivatives of the shape functions N_i ; with respect to x and y , respectively.

1

With

material matrix, D , and the geometric matrix, B , the element stiffness matrix can be

1

obtained by numerical integration as $K = \int_V B^T D B dV$. (3) The

selective integration scheme is adopted in Eq. (3) to avoid the locking problem.

1

The material matrix D is discussed in the next section. 3 MATERIAL MATRIX 3.1 Material matrix before cracking For an orthotropic elastic plane stress problem, the stress-strain relationship is $\{\sigma\} = [D] \{\epsilon\}$. (4) (1 - $\nu_x \nu_y$) G_{xy} γ_{xy} where E_x , ν_x , and E_y , ν_y are the moduli and Poisson's ratios in x and y directions, respectively; G_{xy} is the shear modulus in x - y plane. In the shell element, the in-plane strains can be calculated from the curvatures and the mid-plane strains as $\{\epsilon\} = \{\epsilon_0\} + \{z\} \{\kappa\}$. (5) 4.1 Slabs supported on four edges with corners free to lift (Series II) 12 The series II of the experiment involved 3 panels of 152.4mm thick slabs loaded monolithically through 356mm column stubs. The slabs were simply supported at four edges with the corners free to lift. The slab details are shown in Table 1. Specimen Dimension Dept Concrete Reinforcement s (mm) h f'_c (MPa) E_c (MPa) f_t (MPa) ρ % ρ % 1 (m17m.6) A-4 1828.8 x 1828.8 x 152.4 26.2 24449 332.7 0.6 1.2 A-5 1828.8 x 1828.8 x 152.4 114.3 27.8 25212 321.7 1.2 2.5 A-6 1828.8 x 1828.8 x 152.4 114.3 25.1 23947 321.7 1.2 3.7 Table 1: Details of slabs in series II 1 $\epsilon_x = 0$, $\epsilon_y = 0$ Figure 1: Computational modelling of slabs A quarter of slab is modelled using 121 nodes and 25 elements as shown in Figure 1. The loadings were applied equally at nodes 1, 2, 12 and 13 (position of column stud). Since only a quarter of slab is modelled, the rotation angle θ_y and the displacement v

1

1

1

5

6

5

4

_____IL_____LI_____LI_____L_____LI_____LI_____,I 5 10 0 • .
5 _ • • 1(! 0 5 10 1t CenIJaI deflection (mm) Figure 2:Load-centraldeflection curves of slabs in series II a.
Deflection distribution at early stage b.Deflection distribution near failure Figure 3:Typical deflection
dsitributions 4.2 Slabs supported at four corners (Sarin IV)12 The series IV involves one slab supported on

four corners and loaded through a 254mm column stub. The details of the slab are shown in Table 2. Similarly,

a quarter of the slab is modeled

1

with 121 nodes and 25 elements and the symmetric boundary conditions are applied to the nodes on lines test result in Figure 4. The predicted strength conforms to the experimental result while the predicted $\sigma = 0$ and $\tau = 0$. The obtained load versus central deflection curve are plotted and compared with the central deflection is larger than the experimental observation. Specimen Dimensions (mm) Depth (mm) f_c (MPa) Concrete E_c (MPa) f_y (MPa) Reinforcement p_o (%) A7a 1828.8 x 1828.8 x 152.4 114.3 28.5 25293 321.7 1.2 2.5 300kN 200kN 100kN Table 2 Details of slab A7a in series IV

Figure 4: Load-central deflection curves for slab in series VI

4.3 Slabs supported on four edges with corners free to lift (Sarin VIII) In this work, 5 slabs in series VIII are also selected to analysis. They are loaded through 254mm column stubs, and simply supported at four edges with the corners free to lift. There is no compression steel and the tension steel reinforcement ratios range from 0.5% to 3.0%. For the slab DEH 812, two rows of vertical stirrups with cross sectional area of 1419mm² were used, and the shear reinforcement ratio is about 0.57%. The slab details are shown in Table 3. Again, a quarter of the slab is modelled with 121 nodes and 25 elements and the symmetric boundary conditions are applied at lines $x = 0$ and $y = 0$. The obtained load versus central deflection curves are compared with the test results in Figure 5. Specimen Dimensions Depth Concrete Reinforcement (mm) (mm) f_c (MPa) E_c (MPa) f_y (MPa) p_o (%) - DEHB02 1828.8 x 1828.8 x 152.6 114.3 47.6 32978 320.6 0.5 - DEHB04 1828.8 x 1828.8 x 152.6 114.3 47.7 33013 303.4 1.0 - DEH 809 1828.8 x 1828.8 x 152.6 114.3 43.9 31670 341.3 2.0 - DEH B14 1828.8 x 1828.8 x 152.6 114.3 50.5 33968 325.4 3.0 DEH 812 1828.8 x 1828.8 x 152.6 114.3 45.9 32384 331.6 0.57 3.0 Table 3 Details of slabs in series VIII 800kN

Figure 5: Load-central deflection curves for slab in series VIII

DEHB14

3

Figure 6: Load-central deflection curves for slab in series VIII

DEHB09

7

J

Figure 7: Load-central deflection curves for slab in series VIII

DEHB14

2

DEHB04 1 | -D-EHso / -moael - **-1** - - | model , |||||t|||t|||t|| _____|_
____Li _____ | _____Jt |||||t||||t||||t||||| -:----: \DEH12---:---- : **1**:
Expeiment : : --- --, -- -|------ | ---- TI -----| Experirnen ----- --
-- -----|------|-----|-----

Figure 5 Load-central deflection curves for slab in series VIII In experiment, slabs 809, 812 and 814 are observed to fail by punching shear. The predicted strengths and central deflections generally agree with the test results. For slabs 802 and 804, the numerical results still suggest a shear failure; however, they are actually failed by flexure in the experiment. It shows that, the proposed method maybe only applicable for the slabs subjected to shear failure

5 CONCLUSIONS

In this work, efforts have been made to predict the failure of RC slabs using the FE analysis based on the effective stiffness approach. The non-layered form of the 9-node heterosis shell element is used and the degradation of material matrix due to concrete cracking is reflected by the stiffness reduction factors. In order to predict the failure of the slabs, a softening curve for the bending and shear stiffnesses was proposed based on an empirical failure criterion for RC slabs under bending and shear. The stiffness reduction factors defined by Polak⁵ are modified accordingly to consider the further degradation of the stiffnesses due to steel yielding and shear failure of the concrete. The model parameters CM and CQ in the softening curve are set to be 3.3 and 1.6, respectively, by trial and error method. Three series of RC slabs were analysed using the proposed method. The computed deflection responses and shear strengths are agreeable with the test results for the slabs subjected to shear failure. Further work is needed to

predict the deflection and the strength of slabs

1

subjected to flexure. REFERENCES [1] J. Jiang and F. A. Mirza, "Nonlinear analysis of reinforced concrete slabs by a discrete finite element approach", Computers and Structures, 65(4), 585-592, (1997). [2] H.W. Song, S.H. Shim and K.J. Byun, "Failure analysis of reinforced concrete shell structures using layered shell element with pressure node", ASCE Journal of Structural Engineering, 128(5), 655-664, {2002}. [3] S. Teng, Y. Liu and C.K. Soh, "Flexural analysis of reinforced concrete slabs using degenerated shell element with assumed strain and 3-D concrete model", AC/ Structural Journal, 102(4), 515-525, (2005). [4] W.Y. Wang and S. Teng, "Fintie-element analysis of reinforced concrete flat plate structures by layered shell element." ASCE Journal of Structural Engineering, 134(12), 1862-1872, (2008). [5] M.A. Polak "Effectvie stiffness model for reinforced concrete slabs", ASCE Journal of Structural Y. Liu, J. Chandra and S. Teng Y. Liu, J. Chandra and S. Teng Y. Liu, J. Chandra and S. Teng Y. Liu,J. Chandra and S. Teng Y. Liu, J. Chandra and S. Teng Y. Liu, J. Chandra and S. Teng

S. Teng 313 31 4 31 5 31 6 31 7 31 8 31 9 320 321