DAMAGE INTENSITY CLASS FOR REINFORCED CONCRETE BEAM-COLUMN JOINT SUBJECTED TO LATERAL CYCLIC LOADING

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

UNIVERSITY OF MALAYA
ORIGINAL LITERARY WORK DECLARATION

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Matric No: **17020558/1 / KHA160043**
Name of Degree: **Doctor of Philosophy (Ph.D.)**

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Field of Study: **Structural and Dynamic Engineering (Civil Engineering)**

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DAMAGE INTENSITY CLASS FOR REINFORCED CONCRETE BEAM-COLUMN JOINT SUBJECTED TO LATERAL CYCLIC LOADING

ABSTRACT

The 2015 moderate earthquake that occurred in Ranau, Sabah, Malaysia had damaged more than 60 numbers of non-seismic designed reinforced concrete (RC) buildings from minor to severe damages. These damages were caused by lack of shear links confinement and insufficient anchorage length, particularly on the RC beam-column joint (BCJ) of the buildings. Apart from high-rise buildings, almost all of the existing buildings in Malaysia are non-seismically designed, thus the seismic performance of the buildings in resisting future earthquakes are of concern by the government/public, building owners and local researchers after the destructive earthquake in Ranau. Therefore, an appropriate assessment method is needed to predict the damage level of the existing and new RC structures, thus it may increase the preparedness level for future earthquakes. The damage intensity (DI) class is one of the useful structural assessment methods in evaluating the damage level of the structure based on its structural design under certain loadings. However, the currently available DI class from the literature are limited to vertical static loading only. Thus, there is a need to develop a DI class for lateral cyclic loading as simulating the earthquake loading. Hence, this thesis aims to develop an ANN chart model of DI class for RC beam-column joints, with and without seismic consideration based on lateral cyclic loading and to compare this with the existing DI chart for static load from the Acoustic Emission (AE) method. In phase 1, a total of 7 specimens were designed, prepared and tested to investigate the effects of shear links and anchorage length towards the structural performance and cracking behaviour of RC BCJ under lateral cyclic loading. The AE monitoring was carried out simultaneously during the lateral cyclic loading test to assess the AE signal such as AE hits, AE amplitude, rise time, counts and duration during the crack formation in every drift ratio (DR) level. In phase 2, the specimens design parameters, lateral cyclic loading results and the subsequent AE signals were used as the input parameters for the development of the ANN crack width prediction models and DI class. The observation shows that the additional shear link provision has shown a significant effect on the strength up to 55% compared to the application of anchorage length, hence became the main factor in reducing crack width. In the AE analysis, the higher numbers of shear link provision had indicated that the development of the crack within the specimen is slower compared to other specimens and it does not fail at the maximum DR level. From the ANN results, the Support-Vector Machine (SVM) – dot with root mean square error (RMSE) index performance crack width prediction model has shown the lowest error between the experimental and predicted data up to 5% thus being selected among other prediction models. The DI class has been developed in associated to damage index and response index for every specimen. Naïve Bayes (NB) Kernel classifier model was selected as it shows the highest accuracy and precision up to 98% which is compatible with the experimental results compared to deep learning (DL) and SVM classification model.

Keywords: RC beam-column joint; Acoustic emission; Lateral cyclic loading; Shear link aspect; Anchorage length aspect; ANN prediction models

KELAS INTENSITI KEROSAKAN UNTUK SAMBUNGAN RASUK-TIANG KONKRIT BERTETULANG YANG DIKENAKAN PEMBEBANAN BERKITAR SISI

ABSTRAK

Gempa bumi sederhana pada tahun 2015 yang berlaku di Ranau, Sabah, Malaysia telah menjejaskan lebih daripada 60 buah bangunan struktur konkrit bertetulang (RC) bukan-seismik dari kerosakan kecil hingga teruk. Kerosakan ini disebabkan kekurangan bilangan ruang pautan ricih dan panjang penambat yang tidak mencukupi terutama pada sambungan rasuk-tiang (BCJ) RC bangunan. Selain bangunan bertingkat tinggi, hampir semua struktur yang sedia ada di Malaysia adalah reka bentuk yang tidak seismik, oleh itu prestasi seismik pada bangunan-bangunan ini untuk mengelakkan daripada bencana gempa bumi pada masa depan telah menjadi perhatian kerajaan/orang awam, pemilik bangunan dan penyelidik tempatan sejak gempa bumi yang berlaku di Ranau. Oleh itu, kaedah penilaian yang sesuai diperlukan untuk meramalkan tahap kerosakan struktur RC yang sedia-ada dan baru, sehingga dapat meningkatkan tahap kesiapsiagaan untuk gempa pada masa depan. Kelas intensiti kerosakan (DI) adalah salah satu kaedah penilaian struktur yang berguna dalam menilai tahap kerosakan struktur berdasarkan reka bentuk strukturnya mengikut beban tertentu. Walau bagaimanapun, kelas DI yang tersedia mengikut kajian literatur hanya terhad kepada pembebanan statik menegak sahaja. Justeru, terdapat keperluan untuk membangunkan kelas DI untuk pembebanan berkitar sisi sebagai mensimulasikan beban gempa bumi. Oleh itu, tujuan tesis ini adalah untuk membangunkan model carta ANN bagi kelas DI untuk sambungan rasuk-tiang RC, dengan dan tanpa pertimbangan seismik berdasarkan pembebanan berkitar sisi, dan membandingkannya dengan carta DI yang sedia ada untuk beban statik dari Kaedah Pelepasan Akustik (AE). Pada fasa 1, sebanyak 7 spesimen telah direka, disiapkan, dan diuji untuk menyiasat kesan pautan ricih dan panjang penambat terhadap prestasi struktur dan keadaan retakan RC BCJ di bawah pembebanan berkitar sisi. Pemantauan AE dilakukan secara serentak semasa ujian pembebanan berkitar sisi untuk menilai isyarat AE seperti hit AE, amplitud AE, waktu kenaikan, kiraan dan tempoh semasa pembentukan retak di setiap peringkat nisbah drift (DR). Pada fasa 2, parameter reka bentuk spesimen, hasil pembebanan berkitar sisi dan isyarat AE berikutnya digunakan sebagai parameter input untuk pembangunan model ramalan lebar retak ANN dan kelas DI. Pemerhatian menunjukkan bahawa penambahan pautan ricih telah menunjukkan pengaruh yang signifikan terhadap kekuatan sehingga 55% dibandingkan dengan penggunaan panjang penambat, oleh itu ianya menjadi faktor utama dalam pengurangan lebar retakan. Dalam analisis AE, jumlah penyediaan hubungan ricih yang lebih tinggi telah menunjukkan bahawa pembangunan retakan dalam spesimen lebih lambat dibandingkan dengan spesimen lain malah tidak gagal pada tahap DR maksimum. Dari hasil ANN, model lebar retak ‘Support-Vector Machine (SVM) - dot with root mean square error (RMSE)’ menunjukkan ralat terendah antara data eksperimen dan ramalan sehingga 5%, maka dipilih antara ramalan model lain. Model DI telah dikembangkan bersama dengan indeks tenaga dan indeks kekuatan untuk setiap spesimen. Kelas DI telah dibangunkan mengikut skala indeks kerosakan dan indeks tindak balas untuk setiap spesimen. Model pengkelasan Kernel Naïve Bayes (NB) dipilih kerana menunjukkan ketepatan yang tertinggi sehingga mencapai 98%, justeru, sama dengan analisis kerosakan dari hasil eksperimen dibandingkan dengan model klasifikasi ‘Deep Learning’ (DL) dan SVM.

Kata kunci: RC sambungan rasuk-tiang; Pelepasan akustik; Pembebanan berkitar sisi; Aspek pautan ricih; Aspek panjang penambat; Model ramalan ANN

ACKNOWLEDGEMENTS

First and foremost, I would like to sincerely thank and dedicate this work to my parents for their unconditional support for my life. I also would wish to express my great appreciation to Dr. Tan Chee Ghuan and Associate Professor Dr. Zainah Ibrahim for guiding and continuously providing me with the knowledge required to conduct the research successfully besides sharing the experience of the research and excitement of discoveries. Their faith and encouragement kept me steadfast in the process of acquiring knowledge. Besides that, my profound gratitude to Professor Dr. Ahmed Hussein Kamel Ahmed Elshafie for providing and guiding me in developing Artificial Neural Network (ANN) knowledge, and also to all Professors, Associate Professors and Senior Lecturers of the Department of Civil Engineering for supporting the research work in every possible way to ensure its successful completion.

I would like to express my sincere gratitude to Mrs. Radha Renganathan for her contribution to editing and proofreading the thesis. I would like to extend my thanks to my friends Dr. Ramesh, Dr. Akter Hosen and Mr. Haider for their kind help in this research work. Further extend my sincere thanks to laboratory assistants and technicians namely, Mr. Khairul Anwar, Mr. Zulkifli, Mr. Shahrul, Mr. Sreedharan and Ms. Alfi who have contributed significantly to this research. Above all, I would like to thank my dearest friends and family members, who have been always there for me whenever I faced obstacles due to my nature of work. Their presence and support gave me the strength and courage to overcome the arduous task of completing the thesis thrivingly. Last but not least, a special thanks and endless gratitude to the University of Tun Hussein Onn Malaysia for providing me scholarship under the S.T.A.B. program, hence allowing this research work to perform successfully.

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LIST OF SYMBOLS AND ABBREVIATIONS

A.E	Absolute error
ACI	American Concrete Institute
AE	Acoustic emission
AF	Counts / Duration
AL	Anchorage length at joint
ANN	Artificial Neural Network
$\mathrm{A_s}$	Reinforcement area
ASTM	American society for testing and materials
BCJ	Beam-column joint
BS	British Standard
$\mathrm{C_c}$	Concrete compression strength
$\mathrm{C_t}$	Concrete tensile strength
CW	Crack width
DCM	Ductility class medium
DI	Damage intensity
DL	Deep learning
DOE	Department of Environment's Design Method
$\mathrm{DR}/\Delta_\mathrm{y}$	Drift ratio
EC	Eurocode
H	Column height
HDT	hit definition time
HI	Historical Index
HLT	hit lockout time
JMGM	Department of Minerals and Geoscience Malaysia
l_x	Lateral movement

MMD : Malaysian Meteorological Department

M_w : Magnitude

NB : Naive Bayes

NDT : Non-destructive test

OL_B : Additional shear links spacing at beam

OL_C : Additional shear links spacing at column

P.A : Prediction average

PDT : peak definition time

$Q_{max(+ve)}$: Maximum positive load carrying capacity

$Q_{max(-ve)}$: Maximum negative load carrying capacity

RA : Rise time / Amplitude

RC : Reinforced concrete

RMSE : Root mean square error

SHM : Structural health monitoring

S_r : Severity Index

SSL_B : Shear span for additional shear links at beam

SSL_C : Shear span for additional shear links at column

SVM : Support vector machine

T_t : Tensile bar strength

USGS : United States Geological Survey

LIST OF APPENDICES

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Nowadays, a large part of the civil engineering structures deals with the structures that characterise and have contributed to society. The most important aspects in the design of civil engineering structures are the strength and stability of the constructions. Reinforced concrete (RC) structure fulfils these two criteria and occupies a leading position. RC structure has not only played an irreplaceable role in the last century but also continues to do so in modern constructions (Jones, 1913 : Moussard et al., 2018). RC structure refers to a versatile and strong durable building composite material that can form into a variety of shapes and sizes. The versatility and utility are achieved by combining the best features of concrete and reinforcement bar and thus increasing the tensile strength of the RC structure, as concrete is weak in tension. Hence, in civil constructions, a simple RC structure uses steel bar to provide support in tension areas while concrete provides support in compression areas. However, sudden damage or collapse of RC structures within a very short period (in seconds) happens usually due to unexpected additional loading from earthquake impact (Coburn et al., 1992 : Raghunandan & Liel, 2013). For high-rise buildings, most of the tremors can be deposited at the weakest link of RC members, particularly at the RC beam-column joints that are highly vulnerable to earthquakes. The load-carrying capacity of the columns will be seriously affected if the RC beam-column joints are severely damaged due to an earthquake event.

The past earthquake tremors such as the earthquake at Gujarat in 2001 (Agarwal et al., 2002), the earthquake in Indonesia in 2004 (Ghobarah et al., 2006 : Saatcioglu et al., 2006), earthquake in Japan in 2011 (Abdelnaby & Elnashai, 2014 : Wang et al., 2016) and also the earthquake at Nepal in 2015 (Shakya & Kawan, 2016 : Sharma et al., 2016) across the globe had affirmed that the RC beam-column joints significantly affected the failure behaviour of framed RC structures (Sharma & Bansal, 2019). Generally, RC beam-column joints are among the most critical regions in the moment-resisting reinforced concrete framed structures, as they may suffer serious damages during an earthquake (Mangalathu & Jeon, 2018). They are responsible for resisting lateral loads such as earthquakes, which impact the overall structure integrity (Ganesan et al., 2007). Under strong seismic activities, RC beam-column joints whose function is to maintain the structural integrity of structural systems may experience large deformation. This will significantly reduce their lateral and gravity load-carrying capacity thus leading to partial damage or global collapse of the structure (Uma & Jain, 2006).

Malaysia, assumed to be earthquake-free previously, was impacted with a 5.9 Mw moderate Ranau earthquake at Ranau in 2015. Severe damages were found in existing/old buildings (e.g. in Figure 1.1) which were traditionally designed to resist gravity loads (British Standard) including self-weight, superimposed dead load and strong wind within the elastic range (Alih & Vafaei, 2019).

Figure 1.1: RC beam-column joint damage caused by Ranau earthquake

In these existing buildings, the concrete frames are lightly reinforced, and the RC beam-column joints are insufficiently detailed to resist earthquake forces. This may cause severe joint damage and collapse under reversed lateral displacements of moderate earthquakes. When an earthquake tremor occurs, the RC beam-column joints will be subjected to a large shear force that may cause a sudden decrease in their capacity to sustain loads. The damage in the RC beam-column joints will eventually contribute to the collapse of the building as the seismic demand cannot be dissipated effectively as shown in Figure 1.2 and Figure 1.3. The same situation also occurred in the Chi-Chi earthquake, Taiwan where the catastrophic failure of the structure was caused by the failure of the RC beam-column joint (Tsai et al., 2000). The seriously damaged RC beam-column joint caused the misalignment of the attached beam and column member, thus affecting the distribution of loading and promoting the collapse of the building. In order to improve the seismic performance, modern codes for the design of RC structures specify construction details to avoid high lateral displacement in the joint region. In seismic design, a plastic hinge is accepted to be formed in beam rather than in column to achieve a strong column-weak beam behaviour of RC frame. In addition to the damage in RC beam-column joint, the unpredictable and uncontrollable nature of crack formation in reinforced concrete structures may seriously affect the stability and strength of the structure and thus has been a subject of many studies in recent years (Allam et al., 2012 : Elshafey et al., 2013 : Oh & Kang, 1987 : Wollrab et al., 1996). These types of cracks initiate as narrow and elongated cracks, with openings less than 0.5 mm, often not even visible to the naked eye (Hull, 1999 : Shah, 1990 : Souza, 2019). Although design codes impose limitations on crack widths based on empirical formulae, there is often uncertainty associated with determining the crack width propagation due to cyclic/seismic loads (ACI., 2001 : Institution., 1985 : Normalisation, 2004). Because of the low tensile strength of concrete, cracks are formed under repeated loads. Excessive crack width can reduce the structure's service life by allowing corrosive factors such as high humidity, repetitive moisture penetration, vapour, salt water spray and chemical gasses to penetrate the structure and reach the reinforcement (Allam et al., 2012 : Shinmura & Saouma, 1997). One of the recommended assessment methods is using a damage intensity (DI) class chart to evaluate the performance of the structure based on the design and loading, however, uncertainty arises as the current damage intensity (DI) class chart developed by Shahiron with associates was only focused on vertical static loading, hence there is a need to have a DI class chart for lateral cyclic loading as simulating earthquake loading. Another parameter that involves a part of the DI class chart is cracking width as it is an important tool that influences DI assessment evaluation. The current study shows that an ANN model is yet to be developed for crack prediction and damage classification concerning RC beam-column joint subjected to lateral cyclic loading (Shahidan et al., 2013 : Xu et al., 2017). Therefore, a reliable approach is needed for engineering practice to develop a DI chart model and a crack width prediction model for RC beam-column joint insight including the set of improved structural assessments under cyclic loading recommendation.

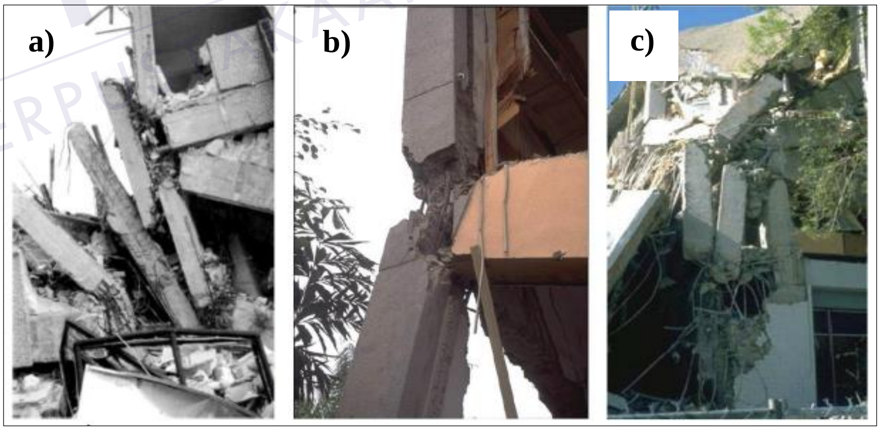

Figure 1.2: Damages of RC beam-column joints in (a) 1999 Izmit, Turkey earthquakes (Scawthorn & Johnson, 2000), (b) 1999 Chi-Chi, Taiwan earthquakes (Tsai et al., 2000) and (c) 1994 Northridge, CA earthquakes (Mitchell et al., 1995)

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LIST OF APPENDICES

List of publication

1) Ganasan, R., Tan, C. G., Ibrahim, Z., Nazri, F. M., Wong, Y. H. (2020). A Case Study on Structural Failure of Reinforced Concrete Beam-Column Joint After the First Significant Earthquake Impact in Malaysia. INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING VOL. 12 NO. 8, 288–302 (Scopus-indexed)

2) Ganasan, R., Tan, C. G., Ibrahim, Z, Bunnori, N. M., Nazri, F. M., Nayaka, R. R. (2020). Crack assessment of RC beam-column joints subjected to cyclic lateral loading using Acoustic Emission (AE): The influence of shear links aspect. Canadian Journal of Civil Engineering. https://doi.org/10.1139/cjce-2019-0578 (In Press – ISI-indexed)

3) Ganasan, R., Tan, C. G., Ibrahim, Z., Nazri, F. M., Sherif, M. M., & El-Shafie, A. (2021). Development of Crack Width Prediction Models for RC Beam-Column Joint Subjected to Lateral Cyclic Loading Using Machine Learning. Applied Sciences, 11(16), 7700 (ISI-indexed)