RGC Ref. No.:
UGC/FDS25/E08/17
(please insert ref. above)

**RESEARCH GRANTS COUNCIL**
**COMPETITIVE RESEARCH FUNDING SCHEMES FOR**
**THE LOCAL SELF-FINANCING DEGREE SECTOR**

**FACULTY DEVELOPMENT SCHEME (FDS)**

**Completion Report**
*(for completed projects only)*

***Submission Deadlines:***
1. *Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.*
2. *Completion report: within **12** months of the approved project completion date.*

## Part A: The Project and Investigator(s)

### 1. Project Title

A Study of Shear Strength and Seismic Performance of Non-seismically Designed Reinforced Concrete Eccentric Beam-Column Joint

### 2. Investigator(s) and Academic Department(s) / Unit(s) Involved

| Research Team | Name / Post | Unit / Department / Institution |
|---|---|---|
| Principal Investigator | WONG Ho-Fai/ Associate Professor | Faculty of Science & Technology/ Technological and Higher Education Institute of Hong Kong |

### 3. Project Duration

| | Original | Revised | Date of RGC / Institution Approval *(must be quoted)* |
|---|---|---|---|
| Project Start Date | 01/01/2018 | NA | NA |
| Project Completion Date | 31/12/2020 | 30/06/2021 | Approved by institute on 28/9/2020 |
| | | 31/12/2021 | Approved by RGC on 6/7/2021 |
| Duration *(in month)* | 36 months | 42 months | Approved by institute on 28/9/2020 |
| | | 48 months | Approved by RGC on 6/7/2021 |

| | | | |
|---|---|---|---|
| Deadline for Submission of Completion Report | 31/12/2021 | 30/06/2022 | Approved by institute on 28/9/2020 |
| | | 31/12/2022 | Approved by RGC on 6/7/2021 |

## Part B: The Final Report

## 5. Project Objectives

5.1 Objectives as per original application

*1. To identify the typical geometry and the critical reinforcement arrangement in non-seismically designed eccentric beam-column joints.*

*2. To study the shear strength and seismic performance of non-seismically designed eccentric beam-column joints under reversed cyclic loading experimentally.*

*3. To study the failure mechanism of eccentric joint with various key parameters by development of numerical simulations using non-linear finite element analysis.*

*4. To establish a sound basis for development of rational and consistent analytical model for predicting the shear strength and seismic performance of eccentric joints.*

*5. To make recommendations for seismic design and retrofitting for eccentric joint in practice.*

5.2 Revised objectives

Date of approval from the RGC: NA

Reasons for the change: NA

*1.*

*2.*

*3. ....*

5.3 Realisation of the objectives
*(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)*

Objective 1:

- The typical geometry and the critical reinforcement arrangement for non-seismically designed eccentric reinforced concrete beam-column joints were identified based on the industrial practice and codes of practice for non-seismic regions of Hong Kong. The key parameters are the joint geometry (location and depth of beam) and amount of stirrup.

Objective 2:

- Fifteen exterior beam-column joints with non-seismically designed details were cast and tested under reversed cyclic loads to investigate the seismic behaviour according to the following parameters: 1) eccentricity between beam and column centrelines; 2) amount of stirrup in joint core; 3) beam-column depth ratio; 4) Anchorage of longitudinal reinforcement. The experimental results enhanced the understanding of the effects of various key parameters on shear strength and seismic behaviour of joints.

Objective 3:

- Non-linear finite element analysis has been employed to develop numerical models of eccentric beam-column joints. The models assisted to investigate the failure mechanism of eccentric beam-column joints with different dimensions and reinforcement details.

Objective 4:

- An analytical model was developed for prediction and evaluation of shear strength and seismic performance of eccentric beam-column joint. In addition, an empirical formula was also developed based on the experimental results.

Objective 5:

- Design recommendations have been proposed based on experimental results and numerical studies.

5.4 Summary of objectives addressed to date

| **Objectives** *(as per 5.1/5.2 above)* | **Addressed** *(please tick)* | **Percentage Achieved** *(please estimate)* |
|---|---|---|
| 1. To identify the typical geometry and the critical reinforcement arrangement in non-seismically designed eccentric beam-column joints. | ✓ | 100% |
| 2. To study the shear strength and seismic performance of non-seismically designed eccentric beam-column joints under reversed cyclic loading experimentally. | ✓ | 100% |
| 3. To study the failure mechanism of eccentric joint with various key parameters by development of numerical simulations using non-linear | ✓ | 100% |

| | | |
|---|---|---|
| finite element analysis. | | |
| 4. To establish a sound basis for development of rational and consistent analytical model for predicting the shear strength and seismic performance of eccentric joints. | ✓ | 100% |
| 5. To make recommendations for seismic design and retrofitting for eccentric joint in practice. | ✓ | 100% |

## 6. Research Outcome

6.1 Major findings and research outcome
*(Maximum 1 page; please make reference to Part C where necessary)*

We have obtained the following major findings:

1.) The joint without eccentricity presented better seismic performance with limited ductility and moderate strength degradation after flexural yielding. With increase of eccentricity, the following behaviours were observed: 1.) the magnitude and ability for energy dissipation are weakened and reduced; 2.) more severe concrete spalling in the joint region; 3.) reduced equivalent viscous damping ratio; 4.) more severe joint shear deformation in the joint. The eccentricity between beam and column centerlines has detrimental effects on the seismic performance of the joints. The small eccentricity of $b_c/8$ has minimal influence. Obviously, significant reductions in stiffness, shear capacity, and ductility were found when the eccentricity increased to $b_c/4$.

2.) The eccentricity caused uneven strain distribution across the joint stirrups within the joint region. The strain of the leg located close to the eccentric side is larger than that on the side far away from the eccentricity. With higher eccentricity, the development of strain in the leg on the eccentric side grows in proportion. The traditional assumption for equal strain across the section should be further reviewed and studied.

3.) The failure mode of joint with eccentricity was shifted to brittle mode (joint shear failure occurred before yielding of beam longitudinal reinforcement) from ductile mode (joint shear failure occurred after yielding of beam longitudinal reinforcement) for those with small or without eccentricity.

4.) To investigate the effectiveness of shear links in the joint cores on the shear strength, specimens with various amount of shear links were prepared and tested. In the study, 0T10, 1T10, and 2T10 stirrups in the joint core, respectively, were provided. The normalised shear strength increased accordingly. Similar to concentric reinforced concrete beam-column joint, increasing the number of stirrups increased the shear strength and improved the seismic performance of the eccentric beam-column joints. The increment of shear strength was directly proportional to the amount of shear reinforcement within the joint core.

5.) To investigate the influence of beam-column depth ratio on the shear strength of eccentric beam-column joints, specimens with various beam-column depth ratio were prepared and tested. In the study, the nominal shear strength decreased with the increment of beam-column depth ratio. The beam-column depth ratio was shown to be an important parameter that affected the seismic performance of eccentric beam-column joints. In current codes of practice, however, it is generally neglected.

6.) The seismic design codes of practice and the Hong Kong code of practice overestimated the shear strength of the non-seismically designed beam-column joints to different extents. Eurocode 2, however, has a relatively good prediction of joint shear strength. Nevertheless, eccentricity reduces its reliability.

7.) The numerical simulation showed good agreement with the experimental results. It assisted to verify the location of stress concentration. Both analytical model and empirical model were developed which agreed well with the experimental results.

*6.2* Potential for further development of the research and the proposed course of action *(Maximum half a page)*

1.) Seismic performance of high-strength reinforced concrete eccentric beam-column joint;

Tall buildings are required to resist high wind loading. In order to satisfy displacement requirement, high-strength concrete (more than 60 MPa) are usually adopted for vertical structural elements e.g. columns and walls. In view of enormous amount of tall building in low to moderate seismic region e.g. Hong Kong, there is an urgent need to extend the study to high-strength concrete eccentric beam-column joints as their shear strength and seismic behavior are still unknown. Specimens with high-strength concrete could be casted and tested under cyclic loads for investigation.

2.) Seismic performance of eccentric joints with slab

In most of the building structures, slabs are always cast together with beams and columns. The study is valuable to extend to investigate the seismic performance of eccentric joints with slab, which would be greatly affected by confinement effect of slab element to eccentric joints. Specimens with slab could be casted and tested under cyclic loads for investigation. The confinement effect could be investigated by non-linear finite element analysis.

## 7. Layman's Summary

*(Describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)*

Seismic performance of non-seismically designed structures has been a hot topic recently. Low to moderate seismic region, such as Hong Kong, has no seismic consideration traditionally, though strong wind design may be incorporated. The seismic risk of these regions are in the case of low probability but high consequence. From post-earthquake investigations, beam-column joint was shown to be one of the most vulnerable regions and its failure induced collapse of many buildings. Seismic performance of non-seismically designed eccentric beam-column joint is, thus, considered to be essential relating to its practical use in existing moment-resisting frame structures. However, there is still lack of consistent approach to evaluate and design such joints from current practice.

The primary goal of the proposed study is to perform thorough investigation to understand the seismic behavior and failure mechanisms of reinforced concrete eccentric beam-column joints with consideration of various key parameters. This goal has been achieved by performing experimental study, numerical simulation and analytical investigation. The research results from this pioneer study provided better understanding of seismic behavior of non-seismically designed eccentric beam-column joint. The design recommendations are expected to reduce the seismic risk and benefit the future development for countries those are threatened by earthquakes.

## Part C: Research Output

### 8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

*(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)*

| The Latest Status of Publications | | | | Author(s) *(denote the corresponding author with an asterisk*)* | Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)* | Submitted to RGC *(indicate the year ending of the relevant progress report)* | Attached to this Report *(Yes or No)* | Acknowledged the Support of RGC *(Yes or No)* | Accessible from the Institutional Repository *(Yes or No)* |
|---|---|---|---|---|---|---|---|---|---|
| **Year of Publication** | **Year of Acceptance** *(For paper accepted but not yet published)* | **Under Review** | **Under Preparation** *(optional)* | | | | | | |
| 2019 | 2019 | | | Wong, H.F. | Discussion on Seismic Performance of Non-Seismically Designed Structures, Civil Engineering Research Journal, Vol 7, issue 3, p. 1 to 3 | Yes 2019 | No | *Yes* | *Yes* |
| 2021 | 2021 | | | Liu, Y., Wong, H.F., Zhang, H.X., Kuang, J.S., Lee, P. M. and Kwong, W.H. | Title: Seismic behavior of non-seismically designed eccentric reinforced concrete beam-column joints Journal: Earthquakes and Structures, Vol 21, No. 6, pp. 613-625. | No | Yes | *Yes* | *Yes* |

### 9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

*(Please attach a copy of each conference abstract)*

| Month / Year / Place | Title | Conference Name | Submitted to RGC *(indicate the year ending of the relevant progress report)* | Attached to this Report *(Yes or No)* | Acknowledged the Support of RGC *(Yes or No)* | Accessible from the Institutional Repository *(Yes or No)* |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| 9/2019/ Korea | Effect of beam-column depth ratio on seismic behavior of non-seismic detailed reinforced concrete beam column joints | The 2019 World Congress on Advances in Structural Engineering Mechanics (ASEM19) | Submitted in 2019 | No | *Yes* | *Yes* |
| 9/2019/ Korea | Effects of eccentricity on seismic behavior of non-seismically designed reinforced concrete beam-column joints | The 2019 World Congress on Advances in Structural Engineering Mechanics (ASEM19) | Submitted in 2019 | No | *Yes* | *Yes* |
| 8/2021/ Korea | Shear strength prediction of concentric and eccentric reinforced concrete beam-column joints | The 2021 World Congress on Advances in Structural Engineering Mechanics (ASEM19) | Submitted in 2021 | No | *Yes* | *Yes* |

**10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning**

*(Please elaborate)*

During the project period, both experimental works and simulation works have involved year four students' contribution as part of their Final Year Project. It can enhance students' ability in conducting experiment and simulation and provide them opportunity to join a RGC funded project which strengthened their academic and research background for job hunting.

**11. Student(s) Trained**

*(Please attach a copy of the title page of the thesis)*

| **Name** | **Degree Registered for** | **Date of Registration** | **Date of Thesis Submission / Graduation** |
|---|---|---|---|
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Note: * The title pages have been submitted in last progress report

**12. Other Impact**

*(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)*

N/A

**13. Statistics on Research Outputs**

| | Peer-reviewed Journal Publications | Conference Papers | Scholarly Books, Monographs and Chapters | Patents Awarded | Other Research Outputs (please specify) | |
|---|---|---|---|---|---|---|
| **No. of outputs arising directly from this research project** | 2 | 3 | NA | NA | Type | No. |
| | | | | | NA | NA |

**14. Public Access Of Completion Report**

*(Please specify the information, if any, that cannot be provided for public access and give the reasons.)*

| Information that Cannot Be Provided for Public Access | Reasons |
|---|---|
| N/A | |