MINISTRY OF EDUCATION AND TRAINING MINISTRY OF CONSTRUCTION
INSTITUTE FOR BUILDING SCIENCE AND TECHNOLOGY

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NGUYEN HONG HAI

RESEARCH ON OUTRIGGER BRACED CONCRETE TALL BUILDINGS SUBJECTED TO EARTHQUAKES IN VIETNAM

DOCTORAL THESIS

HANOI – 2015

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DOCTORAL THESIS SUMMARY

PROFESSION: CIVIL AND INDUSTRIAL
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SUPERVISORS

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CHAPTER 1 – OVERVIEW

1.1 Introduction

The application of existing standards such as UBC, IBC, and EC 8 in seismic resistant design of tall buildings shows many limitations, there for taking the only inter – story drift for appreciating the level of damage is not satisfied. On the other hand, using elastic analysis method with a reduction coefficient (coefficient R in UBC, IBC; coefficient q behave in EC 8) applied to the entire structural system is not reflect a credible analysis result in elastic range, especially for complex structural system or using different materials (concrete and steel). Furthermore, besides the instruction of restrictions such as height or regularity, the above standards do not have appropriate permissions to structural types (erg, outrigger braced tall buildings) or apply the solution advanced techniques (e.g. damping). This makes it difficult for the design of ultra-tall buildings, special structures or applying techniques, new technology.

Performance based seismic design (PBSD) is the new trend in seismic design; especially it is suitable for complex structures or tall buildings. PBSD is using nonlinear techniques for evaluating the behavior of structures and guarantee to satisfy the performance objectives of structures set out based on the seismic resistance level. This method has many advantages such as (1) surveying of structural behavior under earthquake impact more reliably, (2) allowing the application of new materials and advanced techniques effectively, (3) to help achieve the creation of architectural forms by the response reliability of structural solutions and (4) reduce the construction cost.

For complex structures (e.g. tall buildings with outriggers) or structures with new technologies (e.g. damping device), not only using nonlinear pushover method and/or nonlinear dynamic method but also checking and reviewing by experiment in evaluating the overall behavior of structures. Experimental results are not useful for structure itself, but also contribute to theoretical analysis, the design process and detailing for this type of structure that it represents.

The above trend and requirement in analyzing high-rise structures under earthquake load show that research and study the tall buildings under seismic loads by nonlinear method and experiment for outrigger braced tall buildings is the purpose of this thesis.

1.2 Structures in tall buildings trends and future prospects

By reviewing the structural developments in tall buildings, construction material, and new technologies for tall buildings in the world over the last 50 years, it can be concluded:

- The height of the buildings is higher and higher accompanied with various complex factors. Based on the International Journal on Tall Buildings and Urban Habitat (CTBUH) there are 73% of buildings studied in the 2000s adopt a core – outrigger structural system. Of these approximately 50% are constructed with concrete;
- The material using for tall buildings is getting higher in strength;
- Using new technology solution to control the characteristics of buildings.

With such trends, the majority of current design standards do not keep up with the requirements of practical demand. The application of precise current codes do not allow for the best use of structural system and building materials in order to provide safe, predictable performance and optimal design when subjected to strong earthquake ground motions. This is also one of the reasons that researchers and organizations (e.g., FEMA, CTBUH) in the world to propose using performance based seismic design methods, especially the buildings with complex structure.

1.3 Earthquake design philosophy

Damage in the large earthquakes in the 90s of the last century (Northridge - USA, 1994; Kobe - Japan, 1995; Chichi - Taiwan, 1999) showed that if the building structure is designed based on the current method, the collapse probability is very small, the number of casualties caused by the earthquake is not much, but the economic damage caused by the earthquake is too big. According to statistics about the damage caused by earthquakes in the United States during the period from 1988 ~ 1997, the economic damage is over 20 times higher than the total damage of previous 30 years, including indirect damages due to the buildings can not continue to operate normally occupy a considerable rate. From the lessons in the past, it can be concluded the damage directly related to deformation, the design based on the strength is not sufficient.

From the practical results, researchers (mostly in the US) began research performance based seismic design (which has long development in other fields) applied in the design seismic resistant design of buildings. A key feature of this approach is the shift from content design general qualitative goals into specific objectives can be quantified; investors can choose the performance objectives of the building, while emphasizing the analysis and data to satisfy performance objectives in seismic resistance design, creating favorable conditions for innovation in design structure, based on the data (including testing) it can be able to use the new structural system, new techniques, new materials that are not defined in current standards.

The last item, materials, papers, books and technical instructions related to PBSD are listed. These important documents will be helpful reference for working with this area.

1.4 Theoretical and experimental researches on outrigger braced tall buildings

1) Theoretical researches

The study on the outriggers of scientists and institutions in the world can be divided into a number of mainly the following:

a) Research on the impact and optimal location of outriggers

The authors represented in this field include Taranath, Staford Smith and Salim, Hoenderkamp, JR QS Wu and Li, Su Yuan, Alex Coull and Otto Lau. The above researchers primarily based on simplified planar model of core - outrigger. Through a number of assumptions in order to simplify the model, it is be able to offer analytic solutions for the optimal location of the outriggers of the buildings from 1 to 2 outriggers.

b) Research on damped outrigger

The research mainly developed by Arup in putting damping system in the connections between the outrigger and column to increase energy dissipation when subjected to the wind and earthquake load.

c) Design guideline of outriggers braced tall buildings

Currently, only the Chinese code has regulations relating to the structural design of outriggers braced tall buildings. Under this standard, the structure with outriggers has been assigned to skyscraper complex structure. The structural analysis method must be the elastic time history to additional calculations. At the same time, Chinese code recommends using nonlinear pushover analysis or nonlinear time history analysis method accordingly to check the elastic deformation.

In 2012, the International Journal on Tall Buildings and Urban Habitat published technical guidance on the design of outriggers braced tall buildings. The document gives the reader an overview of the structural system with outriggers, the problem should be considered and recommendations in the form of structural design and the specific examples in practice. These issues need to be considered in the design are outlined in the concept for the design aware of issues of concern in practice. Also, when talking about seismic design methodology for outriggers braces tall buildings, document also clarifies the current seismic design standards such as IBC, EC8 are inappropriate when applied to this type of structure and propose to use performance based seismic design.

2) Experimental researches

Currently there were some experimental models in overall structure on the shaking table to serve for the design of buildings. In 2013, Nie Jianguo and Ding Ran had done experimental study on the seismic behavior of K-style steel outrigger truss to concrete core tube wall joints by quasi-static test, cyclic loading at the University Tsinghua.

3) Researches in Vietnam

Regarding the study of structures with outriggers, currently has a number of master's thesis research on this issue, as the study of Nguyen Tat Tam (2010) to calculate reinforced concrete tall building structure subjected to earthquake under TCXDVN 375-2006; the study of Luc Thien Binh (2011) on the application of virtual outrigger in the multi-story structure; or the study of Nguyen Van Thanh (2014) on the core design of reinforced concrete structures in outriggers braced tall buildings, focusing on research to make some simple formula to determine displacement and moment in tall buildings with 1 ~ 2 outriggers.

There are also a number of other related studies as thesis Nguyen The De (2003) published the results of a study on "The rationalization of the structural response of tall buildings under earthquake loading area Ha Noi area"; Vo Thanh Luong's research study on "Dynamic Calculation for frame member in tall buildings under earthquake load with ductility of the material"; Nguyen Quoc Hung study on "Analysis of plane frames considering the softness of joint subjected to horizontal cycle and repeated load "; or study of Le Trung Phong on " behavior coefficient of reinforced concrete structures used in estimating the impact of earthquakes on building".

Experimental study on seismic-resistant design to building in our country is still modest. In 2012, the group of the Institute for Building Science and Technology (IBST) lead by A. Prof. TS. Tran Chung conducted an industrial joint experiment under earthquake loads. Experimental subject is an assembly pre-stressed reinforced concrete frame with two-story subjected to cyclic load. This is the first experiment was carried out in Vietnam with large scale and be done with cyclic load. The results of the research have helped make the hysteresis curves which denote the inelastic behavior and destructive form of frame structure.

1.5 Outline of thesis

It was found that the theoretical study on the overall working principle of the structure with outriggers was made long ago in the world and the formula to calculate the simple plane model has also been launched. However, seismic design for this type of structure is still considered complex and no general procedure applies to all projects. Empirical studies focusing directly on the outrigger area found only one test for the steel rigid joint with K shape and some experiments in vibration table consider the behavior of the overall structure, has not found the experiments relating to outrigger areas for reinforced concrete structures.

In Vietnam, the structural experiments subjected earthquake load in general is very limited. No studies on outrigger structures are experimentally implemented. The structural study of outrigger braced tall buildings is only of the general review of the structural behavior based on linear elastic analysis or calculate based on the design code. In addition, researchers can see that the inelastic behavior of this structure in the form of nonlinear analysis and performance based seismic design is still new in Vietnam. Research topics related to this method is not found.

Therefore, the study of inelastic behavior by theory and experiment with models of concrete outrigger braced tall buildings subjected to earthquake load in Vietnam is the purpose of the thesis. The working of outrigger - column joint is important content of the research program. Applying performance based seismic design, evaluating structural behavior through nonlinear analysis (static and dynamic), taking into account the conditions and geological seismic construction in Vietnam should be done.

2 CHAPTER 2 – PERFORMANCE BASED SEISMIC DESIGN FOR TALL BUILDINGS

This chapter presents deeply important contents of performance based seismic design, including identification method of performance objectives correspond to the seismic hazard, the modeling method and nonlinear analysis, the way to determine the input earthquake in nonlinear analysis. Procedures for performance based seismic design has been set to make the theoretical basis research in order to study the behavior of outriggers braced tall buildings through theoretical and empirical analysis.

2.1 Determining the performance objectives for buildings

A seismic performance objective is defined by selecting a desired building performance level for a given of earthquake ground motion. Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events. If the performance objective is high, the safety of building is improving, but construction costs have increased considerably; if the performance objective set out low, but can reduce initial investment costs but will increase the risk of deterioration of the building, as well as increased maintenance costs.

To determine the performance objective of the building, need to understand the concept of earthquake hazard level; the performance level of building related to the structural performance levels and nonstructural performance levels. These contents are presented in detail in the thesis.

2.2 Nonlinear method for structures

Currently there are several methods of analysis can be used to evaluate the structures for the defined performance objectives. Linear elastic analysis is often used as small earthquakes, whereas the structural components still basically working in the elastic phase. Nonlinear pushover push over analysis or nonlinear time history analysis is often used with strong and very strong earthquakes.

In the framework of the thesis, PhD student have used Ruaumoko software (2D version) to perform nonlinear analysis and in the thesis also presents the theoretical basis of the method of nonlinear pushover analysis used to determine the target displacement (e.g. capacity spectrum method, displacement coefficient method, the method N2) and nonlinear time history methods.

2.3 Modeling in nonlinear analysis

The nonlinear analysis requires one to think about inelastic behavior and the limit state (depending on the strain and force) for the Engineers. In this analysis, the need to define the model behavior of structures that can reflect force – deformation relationships of structures based on strength character and expected stiffness and large deformation. Depending on the type of structure, nonlinear analysis results can be very sensitive to the input parameter assumptions and used models.

Thesis presents some methods of modeling frame member as concentrated plasticity model, distributed plasticity model and force – deformation relationships in nonlinear analysis. At the same time introducing modeling for frame member in Ruaumoko software and elasto – plastic hysteresis rule in structural modeling of investigated building in chapter 3.

2.4 PBSD Procedure for outriggers braced tall buildings

From the studies related to performance based seismic design that are present in the upper part of the thesis, Phd student were aggregated to establish the process design based on this method for engineers to enforce use.

2.5 Summary chapter 2

1. The basic principle of performance based seismic design and the important contents of the nonlinear analysis method were presented. This design method was considered to have many advantages. Compared to strength based seismic design, the biggest difference is to allow assessment of all the building member (both structural and nonstructural) quantitatively at many different levels of earthquake together, even during earthquakes. Through monitoring the process of forming plastic hinges in structure, the designer can proactively control energy dissipation mechanism at will, whereby controlled dangerous destructive forms (overall structural buckling or building collapse) due to the formation of unreasonable plastic hinges.
2. The challenge of this design method is (1) to decide the performance objectives corresponding to acceptance criteria for each structural

member or nonstructural member, (2) determine the hazard level and suitable nonlinear behavior model choice for nonlinear pushover and / or dynamic structural analysis, and (3) finally processed analytical results obtained to assess the performance objectives.

3. Establishing a process of performance based seismic design in order to apply in practical design.

3 CHAPTER 3 – PERFORMANCE OF TALL CONCRETE BUILDINGS WITH OUTRIGGERS SUBJECTED TO EARTHQUAKE IN VIETNAM

3.1 Introduction

It can be said that there have not unique procedure in the design of high-rise outrigger structures, but important issues such as the recommendations of the CTBUH for each specific project. To solve the problems mentioned in Chapter 1 of the performance of high-rise buildings with outrigger in the conditions of Vietnam, this chapter focuses on analyzing some specific structures in order to clarify the following:

1. To study the appropriateness of spectra selection in accordance with TCVN 9386: 2012 for nonlinear analysis;
2. To study the effect of outrigger stories (location, stiffness) to behavior of buildings;
3. Verify the performance objectives within collapse prevention limit. The analysis results are compared with experimental results presented in Chapter 4.

3.2 Prototype structure used for analyses and testing

In general, actual building structures are in 3D dimensions. Structural plan layouts define their “space” behaviors when subjecting lateral loads, such as earthquakes. Theoretically, for earthquake loads, structures should be designed to withstand the motions coming from any directions. In practice, structures are often designed to resist seismic loads in certain directions, usually in two orthogonal directions, depending on the layout of main bearing structures. For symmetric structures, the analysis for studying of global structural behaviors could be implemented through simplified models - 2D models. In this case, the important characteristics of the presented structures under consideration (such as load paths, distribution of deformation over the height, plastic hinges formation and mechanism formation, etc. ...) can be evaluated through simple 2D model.

Main issues of the research relate to: force distribution characteristic – load paths – among lateral load resisting systems (perimeter columns, outrigger beams and cores), lateral displacement, plastic hinge formation, energy dissipation in the structure, local behavior of column-outrigger connections.... The influences of “space” behavior of the structure are beyond the scope of research. Hence, structural model used for analytical and experimental studies is determined as simple 2D models. Carrying out biaxial cyclic reversal load tests is too complex for the study conditions. Thus, tests shall be implemented as uniaxial cyclic reversal method. The structural model used for study is designed based on the reference of some typical tall and super-tall buildings in Vietnam. Structural system is simplified with following main parameters:

Table 1: Parameters of the structure

Parameters		**Value**
Frame	Story No.	55 stories
	Story height	4m typical, 6.5m for the outrigger story (story 34)
Section dimensions	Core	t=1200mm
	Column	bxh=1500x2500, 1500x1800, 1200x1500
	Beam	bxh=2000x500
	Outrigger	bxh=800x6500
Materials	Concrete	f’c = 28 MPa
	Rebar	fy=490 MPa
Loads	Self weight	Automatically taken into account by analysis software
	Superimposed load	1.1 kN/m^2 superimposed load and 0.5 kN/m^2 for ME
	Live load	2.0 kN/m^2 (office)
	Wind	Wind zone IIB, terrain type B
	Earthquake	a_{gR} = 0.103g, soil type D
Design standard		ACI 318-05

3.3 Selection of seismic motions appropriate to Vietnam conditions for nonlinear analysis

Determination of target displacement for nonlinear pushover analysis as well as adjustment of displacement spectra should be based on standard displacement spectra. Through analysis, comparing acceleration spectral and spectral displacement in TCVN 9386: 2012 and other standards such as ASCE 7-10 (USA), GB 500 011 (China), the shape of acceleration spectrum between different standards are matching, but the shape of the spectral displacement (Figure 3-7) are much different. It can be seen that the curves separate at period from 2s.

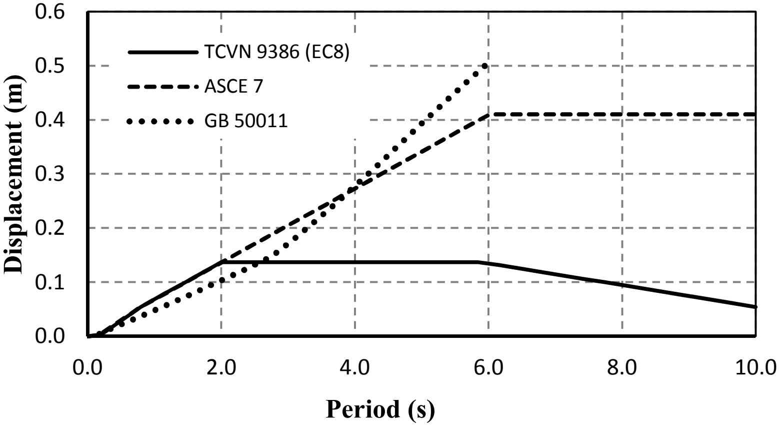

Figure 3-7: Displacement spectra with respected to some selected codes

This variability is also mentioned by other researchers in the world. Research by Bommer, Sinan Akkar shows that displacement spectra EC8 (TCVN 9386) gives too low values, especially for medium sections and long period, the main reason is selection of T_D = 2s. The lower value of corner period for displacement spectral provides analysis results in unsafe manner.

Target displacements are calculated for two buildings based on nonlinear pushover analysis. The results show that top displacement determined in accordance with TCVN 9386 displacement spectra is unreasonable (too small) with respected to the building scale, while the result estimated based on ASCE 7-10 spectra is more appropriate. Besides, the above discussion is also true for time-history analysis. Based on the above analyses, appropriate application of displacement spectra in accordance with TCVN 9386 spectrum (EC8) to determine target displacement (for pushover analysis) and adjustment of ground motions (for time-history analysis) is given for tall building (having long period). In this case, it is recommended to use displacement spectra in according to ASCE 7 for analysis, unless more accurate seismic hazard assessment has been done.

3.4 Effect of outrigger story to structural behavior

For purposes of investigating effects of outrigger story to building behavior, two computer program are set up to calculate the target displacement and behavior factor based on N2 method (see Chapter 2), with the input data is stress-strain relation obtained from nonlinear pushover analysis.

1) Effect of outrigger story location

To verify influences of outrigger story locations, analyses are carried out with different levels of outrigger locations: 5, 10, 15, 20, 25, 30, 34, 40, 45, 50 and roof. Story drifts shown in Figure 3-29 are determined based on TCVN 9386: 2012 associated with ground acceleration $a_g = 0.1g$ and ground type D.

Analysis results show that structure displacements vary greatly when changing the position of the outrigger story. Peak displacement can be reduced to 2.5 times. Displacement is smallest when the outrigger stories located in the 25, 30 and 34 (red line) floors. Hence, buildings with one outrigger story, it is most effective when outrigger story location is in the middle along the building height. This is consistent with previous research that has been published.

2) Influence of stiffness outrigger

Investigation is carried out with the same structural model with outrigger in story 34, and cross-section dimensions are changed from 0.8x1.0m to 0.8x8.0m.

Pushover analysis results for various outrigger dimensions are shown in Figure 3-33. Influence of outrigger stiffness to the building capacity curve is significant. The more stiffness of outrigger, the more lateral resisting capacity is obtained, and top displacement is reduced. The influence is most significant when plastic moment of the outrigger is larger than sum of that of lower and above outrigger columns. For the investigated structure, this happens with outrigger sizes of 0.8x3.5m and larger.

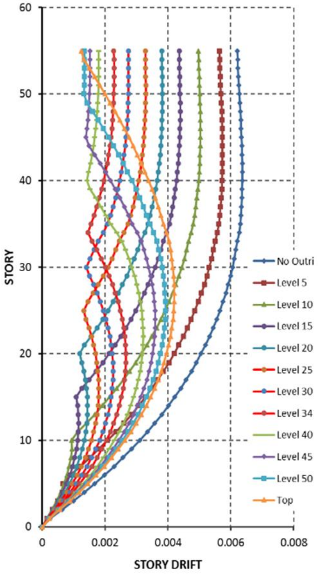

Figure 3-29: Story drift with respected to outrigger locations

3) Behavior factor

Behavior factors of investigated structure with respected to outrigger stiffness is shown in Table 3-6. It can be seen that behavior factors tend to increase as the stiffness of the outrigger increases, or in other words increasing the ductility of the structure. Meanwhile, when carrying out linear elastic analysis the behavior factor, taking into account the vertical irregularity, is set to a single value (q = 3.12).

Thus, for complex structures with irregularity, the selection of behavior factor used for traditional analysis methods (e.g. response spectrum analysis) may not reflect true behavior of the structures. Therefore, in these cases it is recommended to carry out nonlinear analyses to verify the structural behavior.

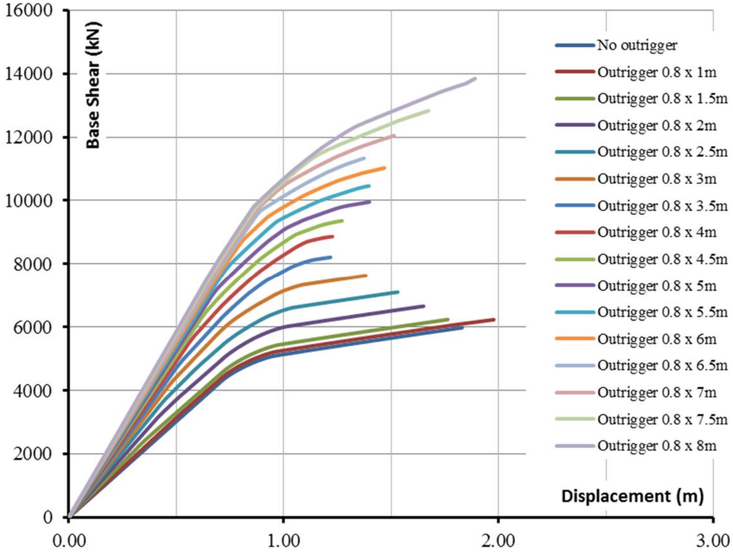

Figure 3-33: Capacity curves with respected to outrigger sides

Table 3- 1: Behavior factors with respected to outrigger sides

No.	Outrigger side	*q*	No.	Outrigger side	*q*
1	No outrigger	2.01	9	0.8x4.5m	2.46
2	0.8x1.0m	2.17	10	0.8x5.0m	2.76
3	0.8x1.5m	2.12	11	0.8x5.5m	2.83
4	0.8x2.0m	2.21	12	0.8x6.0m	3.02
5	0.8x2.5m	2.31	13	0.8x6.5m	2.92
6	0.8x3.0m	2.29	14	0.8x7.0m	3.22
7	0.8x3.5m	2.18	15	0.8x7.5m	3.52
8	0.8x4.0m	2.30	16	0.8x8.0m	3.87

3.5 Evaluation of seismic performance by PBSD

The verification of performance objectives in collapse prevention condition based on PBSD presented in Chapter 2 is implemented. Input seismic ground motions include 07 records, in which 5 records are adjusted from real record (taken from the strong earthquake database from PEER) and 02 artificial records (created by software Shake91, taking into soil characteristics in Hanoi). All records are adjusted to fit ASCE 7 spectra, corresponding to very strong earthquake (probability of exceeding 2% in 50 years, i.e. to the return period of 2475 years).

From analytical results, some conclusions are given bellow:

- Axial forces, shear forces and bending moments of the columns connected to outriggers change dramatically compared to that of columns at other floors. Therefore, structural elements at outrigger stories should be especially considered when designing structures of this type;
- Design to ensure load paths (and interact action) from outriggers to perimeter columns is critical issues for designing of the structures. This is one of the main reasons to carry out the experimental study in this research, which is presented in chapter 4;
- From energy distribution curve and verification of structural performance objectives (top deflections, story drift, and plastic rotations) it is shown that the structure is just in beginning of inelastic stage. The structure can still be optimized.

3.6 Outcomes of Chapter 3

1. Acceleration and displacement spectra in TCVN 9386: 2012 are not appropriate to determine the target displacement in nonlinear pushover analysis or to fit ground motions in time-history analysis in long period range (applicable to tall/super-tall buildings). The ASCE spectrum is recommended.
2. Acceleration spectral, taking into account soil amplification effects associated with Hanoi soil condition type D, is studied. Compared with the EC8 (TCVN 9386) acceleration spectra, obtained spectra values are larger for the period smaller than 1.5s, however the values are smaller for longer periods. However, in order to comprehensively assess the effects of local soil conditions to specific structure behavior, there should be further study. It is beyond the scope of the thesis.
3. For the investigated structure, the most optimized location of the outrigger is from 0.5H to 0.6H (H is the height of the structure) in

term of top displacement and story drift. In addition, the analysis shows that when the outrigger story is available (floor 34), top deflection reduces by 2.5 times in comparison with the case of non outrigger.

4. Outrigger stiffness greatly affects to global behavior of the structure. The more stiffness of the outrigger, the large the shear forces, resulting in higher level of sudden change in element internal forces. Hence, it is necessary to properly adjust outrigger stiffness in order to satisfy global displacement requirement and to limit internal forces of structural elements of the outrigger story at reasonable level.
5. Through static pushover analysis, behavior factor ranges from 2.17 to 3.87, relatively different from the initial value ($q = 3.12$) selected for linear elastic analysis. It can be seen that for tall buildings with outriggers, assessment of structural behavior based on nonlinear analyses is important.
6. Time-history analyses demonstrate process of plastic hinge formation, associated with outrigger modification and variation of input ground motions. In addition, performance assessment of the structure based on criteria of global displacement, element rotations and energy dissipation characteristics shown that the investigated structure is just beginning of inelastic stage. The structure satisfies assessment criteria. From nonlinear pushover and time-history analysis results, the structure could be optimized. However, the issue of the research scope.

4 CHAPTER 4 – MODEL TESTS OF COLUMN-OUTRIGGER CONNECTION

4.1 Purposes and objectives of the experimental study

The purpose of the experimental study is to study performance of the column-outrigger connections when subjected to earthquakes, clarifying the following issues:

- Performance (strength, stiffness and ductility) of connections: when subjected to earthquakes, structures should have sufficient capability of energy absorption, under inelastic deformation without degrading strength and stiffness to the point of destabilizing and losing integrity of the structures.
- Evaluating of failure modes of the column - outrigger connections.
- Evaluating, verifying elasto-plastic hysteresis rules used for modeling of the connections in the nonlinear analyses.

The tests consist of column-outrigger connections with model scale ratio of$S_l = 5.0$. Considering capability of the IBST earthquake laboratory, testing method was determined as uniaxial cyclic reversal quasi-static test.

4.2 Analysis of prototype and determining model scale

The models are designed based on 55-story planar reinforced concrete structure with one outrigger located at level 34, which is presented in chapter 3. To determine test setup and appropriate model scale, forces and deformations of the elements comprising the connections are studied. Theoretical analysis shows the outrigger and perimeter columns are under reversal forces, during the seismic actions. For vertical loads, axial stresses of the columns are about$0.15f'_c$, for earthquake loads the values are between 0 to$0.25f'_c$.

Strength of the prototype structure is preliminarily determined through theoretical calculations. Strength (bending) of the column is about 22.000kNm, corresponding to the axial stress level of 0.2f'c (16.200kN). From the above analysis and considering the capacity of IBST laboratory equipment, appropriate model scale is selected as$\boldsymbol{S_L = 5.0}$.

4.3 Design and detailing of the testing models

The specimens are designed for shear and bending. Shear strength is determined as per ACI 318-05, formula 21.7, equivalent to 272 kN. This value corresponds to the moment at column base of 272kN * 0.79m = 215kNm, greater than column strength (according to ACI 318-05) of 160kN (when axial force equivalent to$0.2f'_c$) or 140kNm ($0.1f'_c$). This is expected that the specimen shall initially fail in bending, but shear effect is noticeable. The strength of specimens verified by the software Response2000, which are calculated as 204kNm and 180kNm, corresponding to push/pull forces on top of the column of 225kN and 254kN, depending on compressive stress $0.1f'_c$ and $0.2f'_c$.

Concrete mix is designed at the IBST laboratory. Coarse aggregate is small stones of 5mm in diameter. Cylinder compressive strengths,f'_c range from 28.5 to 31.9Mpa. Yield strength of rebars are 510Mpa (ϕ14) and 415Mpa (ϕ8). Testing model is shown in the Figure 4-10.

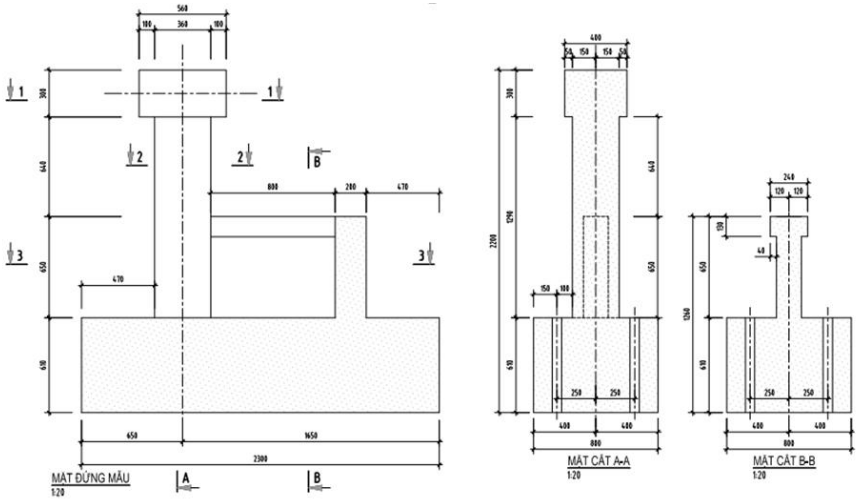

Figure 4-10: Testing model

4.4 Loading protocol

Two testing models C1 and C2 are subjected to loading protocol as follows:

- Vertical loading: Maintain compressive load of 300kN ($0.1f'_c$) for the column C1 and 600kN ($0.2f'_c$) for column C2.

- Lateral loading: Loading procedure proposed by Park (1989) is adopted for the tests of models C1 and C2. The procedure consists of two stages: (1) force-based loading stage and (2) displacement-based loading stage, as shown in the Figure 4-15.

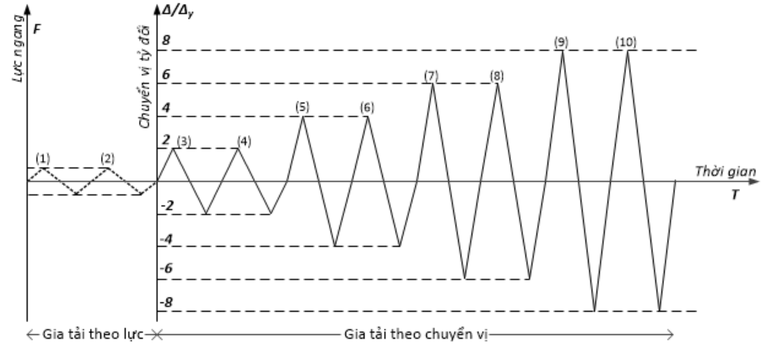

Figure 4-15: Loading protocol

4.5 Experiment results

1) Behavior of the column-outrigger connections

Cracks appear early, but the structures are in elastic stage to the displacement corresponding to drift of 0.7%. Initial stiffness of the C2 specimen is larger than C1, due to difference of axial force levels. More cracks appear and stiffness decrease at drift of 1%. For drift of 1.5%, the cracks widen and spread over the surface of the connections. Steel yields at drift about 1.5%. Cracks appear deep into outrigger. The structure performs stable until drift level of about 2.0%, concrete crushing can be seen. At drift levels of 2.5-2.7%, concrete at column base is completely crushed and spalling, exposing reinforcements. However, until this point hysteresis curve remained stable, although the stiffness and strength decline. At largest displacement corresponding to drifts of 4.4% (C1) and 5.4% (C2) concrete damages expand further into the outrigger zone, especially with the specimen C2. When the experiment stops diagonal cracks formed remarkably, due to the influence of shear stress.

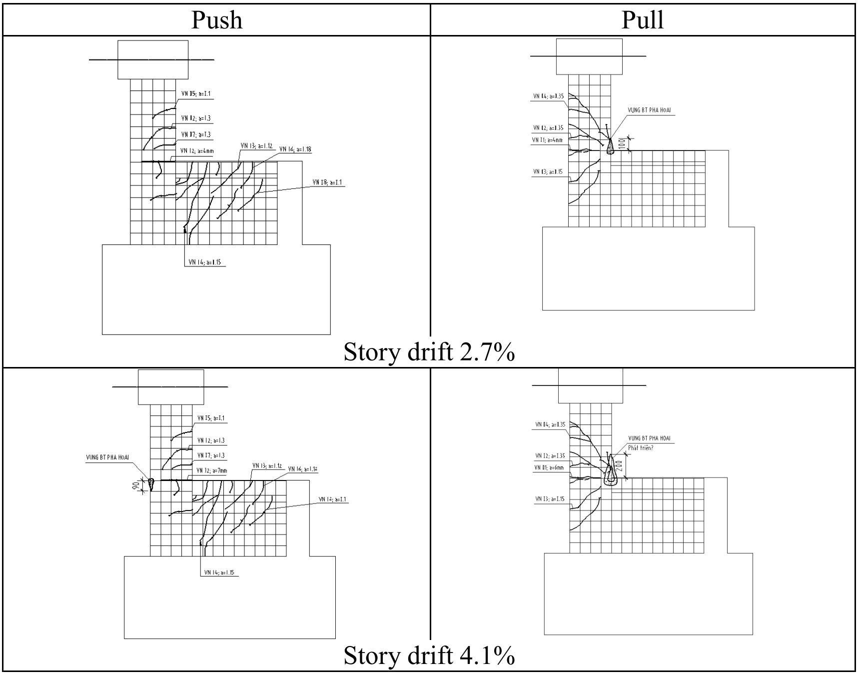

Figure 4-16: Crack pattern – Specimen C2

Figure 4-17: Testing of specimen C1

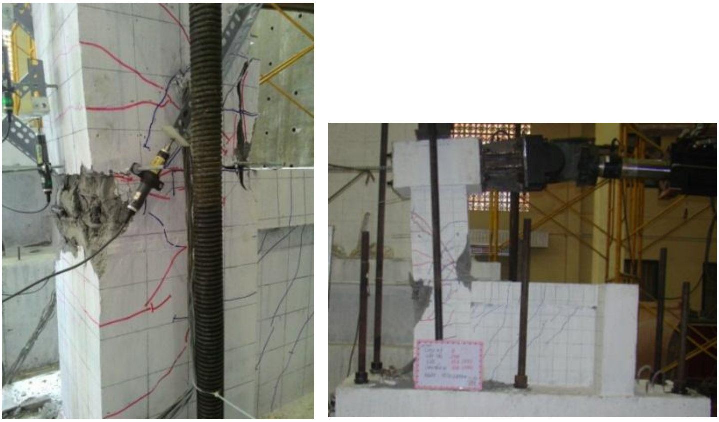

Figure 4-18: Testing of specimen C2

2) *Hysteresis, strength and stiffness degradation*

The hysteresis curves (Figure 4-19, 4-20) represent good energy absorption characteristics and stability of the test structures. Effect of axial stress to the strength of the connections is clearly shown though the results of the experiment. Maximum strengths of the C2 and C1 are 315kN and 247kN, corresponding to compressive stress of 0.1f'c (300kN) and 0.2f'c (600kN). This phenomenon is consistent with theoretical calculations by design codes. Besides, from the experimental curves it can be seen that the strength of the connections in push direction is lower than that of pull directions, 200kN compared to 250kN (C1), and 247kN compared to 315kN (C2). Constrain effect due to the outrigger prevents deformation of columns, resulting in higher strength in this direction. Experimental results also show adverse effects of large compressive forces.

The connections are in elastic stage at displacement value equivalent to drift of ±0.25%. When drift increases, stiffness reduction appears for reduced load cycles. Significant reduction of stiffness happens at drift level of ±1.5% or higher. For specimen C1, strength reduces by 13%, with 40% for the C2. However, when the strength reduction is 20%, the structure is considered to be failed. The higher strength reduction for the C2 compared to the C1 is due to effect of axial stress. Compressive stress of the C2 is 0.2'fc in comparison with 0.1f'c for the C1.

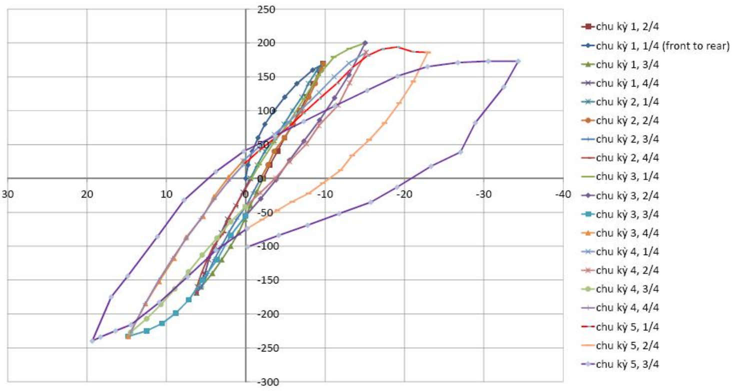

Figure 4-19: Hysteresis curves of the specimen C1

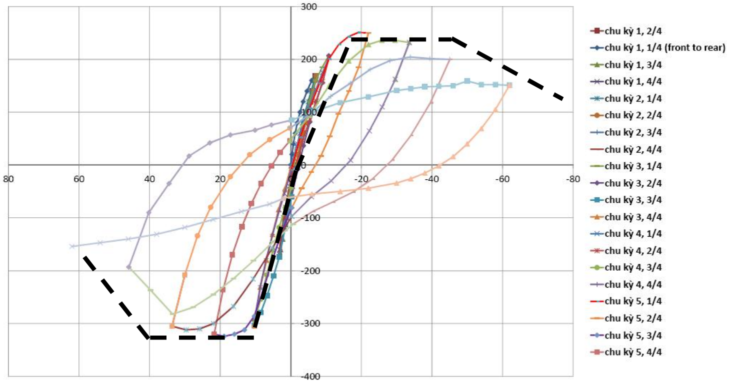

Figure 4-20: Hysteresis curves of the specimen C2

3) Ductility

Ductility of structures are determined as ratio of maximum displacement at failure and displacement at the point of fist yield of reinforcement. According to test results, ductility of the column-outrigger connections are about 2.5 to 2.9. Maximum displacements and yield displacements are 35mm and 12mm, 42mm and 17mm, accordingly to specimens C1 and C2. This shows the influence of the axial force to the ductility of the connections. The connections have higher ductility as axial stress is relatively lower.

4) Performance evaluation of structures

Curvature variations along height of columns C1 and C2 are shown in Figure 4-21 and Figure 4-22. It can be seen the asymmetry of the curvature distributions of the two side, push and pull, due to the asymmetry of the connections. Plastic hinge length of the columns about 200mm, equivalent to 0.25H, where H is the height of the column.

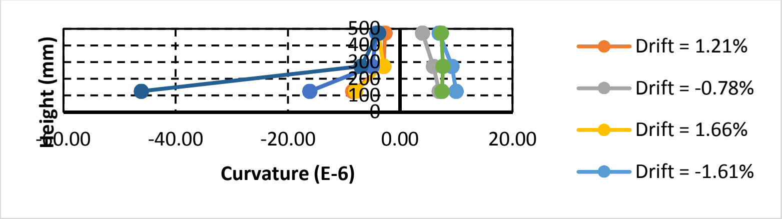

Figure 4-21: Curvatures of the specimen C1

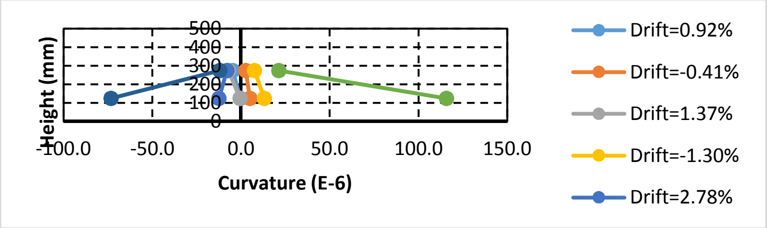

Figure 4-22: Curvatures of the specimen C2

Energy dissipation characteristics of the structures can be evaluated though equivalent viscous damping associated with each loading cycle. The later cycles have higher energy dissipation the precedence. Comparing the viscous damping of the first cycle of the first 4 loading magnitude, it is shown that effect of axial load to the energy dissipation capability of the structures is insignificant.

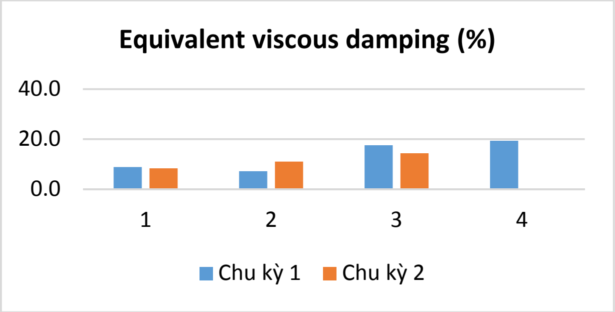

Figure 4-23: Equivalent viscous damping of the specimen C1

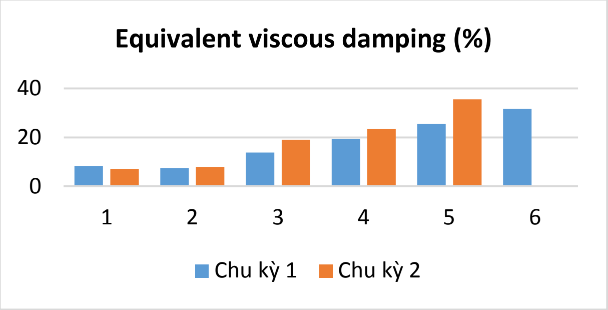

Figure 4-24: Equivalent viscous damping of the specimen C2

5) Evaluations of performance objectives based on experimental results

Allowable average and maximum story drifts corresponding to collapse prevention performance objectives are 3.0% and 4.5%. Experimental results show that up to drift of 4.5%, the structures have good performance. Strength degradations are in allowable limits, 15% to 20% for the C1 and C2, accordingly. Structures are considered to be failed as strength reduction exceeds 20%.

Nonlinear dynamic analysis for the investigated structure shows the rotation at column base of the connections is relative small, about 0.002 rad. At this rotation value, the connection is still in elastic stage. According to test results, reinforcements reach yield strength as rotation of about 0.0025 rad. Connections maintain their strength for the rotation up to about 0.025 rad, satisfying assessment criteria for column structures presented in chapter 2, Table 2.4. The maximum allowable rotation of columns is 0.02 rad.

Thus through proven by experiments showed that, with the link button column-beam design suitable hardware as standard, can ensure these goals with the application features a very strong earthquake (in 2500 years return period) or greater.

4.6 Remarks

From the experimental results, some important remarks can be drawn as following:

- Code adopted design of column-outrigger connections shows good performances in terms of energy dissipation absorption.

Concrete starts crushing at displacement corresponding to drift 2.0%.

- Failure mode is initially bending and shear effect is considerable. Concrete of the outrigger (outside building face) and the column (inside building face) is crushed. Column stirrup spacing should be considered in order to secure stability of longitudinal bars. The issue is particular important to the embedded areas of columns into the outriggers.
- The connection test models have the scale ratio of 2.2, the influence of shear stress is remarkable and diagonal cracks are wide opened at the end of the test. Design for shear is crucial for columns connected to outriggers. This should be more paid attention as the shear span ratio of columns is shorter.
- In these experiments, column ductility is about 2.5.
- Behavior factor is recommended to be properly modified when designing outriggers and connected columns.
- It is recommended to design columns below and above outriggers with high axial stress level in order to avoid premature strength degradation when subjected to strong earthquakes.

CONCLUSIONS AND RECOMMENDATIONS

I. Research outcomes

1) The performance based seismic design (PBSD) is being considered a new trend of seismic-resistant design. In comparison with traditional force-based seismic design methods, the method has advantages in qualitatively evaluation of performance of structures associated with relevant seismic hazard levels and of time-history structural responses during the earthquake motions. The method is especially pertinent for buildings with complex structural system. Proper design of structures, avoiding unexpected damages and unstable schemes, can be implemented by mean of controlling appropriate plastic hinge formation through nonlinear analyses. Structural nonlinear analyses also help to evaluate the behavior factor used in the preliminary analyses in accordance with practice design codes.

2) To establish a PBSD procedure for concrete high-rise buildings, emphasizing on application of the method for design practice in Vietnam.

3) Through literature review and parametric study results, it is shown that acceleration and displacement response spectra in the TCVN 9386:2012 with the corner period of 2s are not appropriate for matching ground motions used for time-history analyses and determining target displacement in pushover analyses for tall buildings. Recommendation of using ASCE 7 spectra as an alternative is given.

4) When creating artificial ground motions for time-history analyses, hard-to-soft soil ground motion amplification effects should be considered. The actual soil conditions at construction site shall be used.

5) To develop a computer program determining target displacement and calculating behavior factor based on capacity curves obtained from nonlinear analyses.

6) Outrigger stiffness should be properly adjusted not only to control lateral displacement but also to limit sudden changes of internal forces of structural elements around outrigger levels, optimizing structural design.

7) To carry out experimental studies of performances of column-outrigger connections. From testing results of 02 specimens, some remarks are given as follows:

    a. Elasto-plastic hysteresis rules can be used for modeling of column-outrigger connections when carrying out nonlinear analyses;

    b. Design the connections with overstrength of shear capacity and sufficient desired ductility. This can be assured though nonlinear analyses, controlling structure strength at a proper level to maintain shear forces while satisfying local ductility and global lateral displacement requirements.

    c. Columns lower and above outriggers should not be designed at high level axial forces in order to avoid premature strength degradation when subjected to large earthquakes.

    d. When designing of the connections, column stirrup spacing should be considered in order to secure stability of longitudinal bars. The issue is particular important to the embedded areas of columns into the outriggers.

II. Recommendations for further studies

1) Research on behavior of concrete structures with outriggers by nonlinear analyses of 3D models provides advantaged explicit results, as well as helps evaluating of structural behaviors when subjecting to earthquakes more comprehensively.

2) Researches on outrigger types and materials such as steel and composite structures should be carried out.

3) Tests with larger scale and more complex models outriggers with connected elements and assemblages (e.g. triaxial tests of column-outrigger connections and full frame outrigger structures) can be

implemented to help more comprehensively understanding behavior of actual structures.

4) Shaking table tests of small scale building models are very good options to examine global behavior and damage formation of outrigger building structures.

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