CYCLIC PERFORMANCE AND STRENGTHENING OF BUILT-UP BATTENED COLUMNS

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DEDICATION

I would like to dedicate this thesis to my beloved parents for their endless support and encouragement.

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In the name of Allah, the most beneficent and the most merciful In preparing this thesis, I was in contact with many people, researchers, and academicians. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Associate Professor Dr. Mohammadreza Vafaei, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Associate Professor Dr. Sophia C. Alih for her guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here. I have learned from them not only how to perform and interpret experiments but also how to think and move the project forward. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. Finally, yet importantly, I would like to express utmost appreciation to my lovely and kind parents and wife for their love, support and encouragements throughout my life.

ABSTRACT

Built-up battened columns have been widely used in steel structures mainly because of providing a higher moment of inertia than solid sections with a similar weight. Despite wide application in steel constructions, the seismic design of these columns has not been well addressed in the literature, and seismic design codes do not provide a specific seismic design guideline for them. On the other hand, past earthquakes have shown that built-up battened columns have been vulnerable against seismic actions mainly because of the plastic deformation in battens, fracture of battens, global buckling of columns, local buckling of web and flanges, and formation of plastic hinges at their bottom panel. Therefore, their seismic behaviour should be investigated, and an efficient strengthening method should be proposed. In this study, experimental works and numerical simulations were conducted to investigate the governing failure modes of built-up batten columns. Besides, the effect of batten's thickness, battens spacing, chord distance and axial load on the ultimate load, ductility ratio, stiffness degradation rate and energy dissipation capacity of built-up battened columns were investigated through quasi-static cyclic loading. This study also proposed a strengthening method through the filling of chords with grout and wrapping it with carbon fibre reinforced polymer (CFRP). Experimental works included four unstrengthen and four strengthened columns with different battens spacing and chord distances. Besides, 210 built-up battened columns with different batten thicknesses, battens spacing, chord distances, axial forces, number of CFRPs layers and number of strengthened panels were simulated in ABAQUS software and subjected to cyclic loading. The obtained results indicated that the bulging of chord webs together with the local buckling of chord flanges were the main reason for the failure of columns. Moreover, built-up columns did not reach their plastic moment capacity because of local buckling in flanges. Furthermore, the columns with 62 mm batten spacing showed a 30% larger ultimate load than that of the column with 550 mm batten spacing. The results also indicated that the columns with 62 mm batten spacing reached 95.91% of their theoretical bending capacity. It was shown that design codes' requirements for batten spacing was not conservative and did not result in an identical safety margin for the bending moment capacity of built-up columns. An increase in the chord distance from 50 mm to 150 mm enhanced the lateral strength of the column by 35%. On the other hand, an increase in the axial force from 0.1Fy to 0.4Fy decreased the lateral strength and ultimate displacement by 24% and 36%, respectively. The displacement ductility ratios of the unstrengthen built-up battened columns were less than two even when subjected to an axial compression ratio smaller than 0.2. The results indicated that CFRP application delays/shifts the local buckling of flanges and bulging of the web to the upper un-retrofitted panels; however, an increase in the number of CFRPs layers did not show any pronounced effect. The retrofitting of columns resulted in a significant increase in the lateral strength and corresponding displacement by 32.15% and 39.34%, respectively, as compared to the un-retrofitted columns. The energy dissipation capacity of retrofitted columns was 66.39% higher than that of the un-retrofitted columns. The retrofitted columns lost 27%, while the un-retrofitted columns lost 52% of their initial lateral stiffness at a drift ratio of 5.0%. In addition, the retrofitted columns were also able to reach their plastic moment capacity and had a displacement ductility ratio larger than two. The outcome of this study helps practice engineers to understand the seismic behavior of built-up battened columns better and provides an efficient retrofitting method for these columns.

ABSTRAK

Tiang bertetulang terbina telah digunakan secara meluas dalam struktur keluli terutamanya kerana ia memberikan momen inersia yang lebih tinggi berbanding seksyen pejal dengan berat yang sama. Walaupun aplikasinya meluas dalam pembinaan keluli, reka bentuk seismik untuk tiang ini tidak dihurai dengan mendalam dalam literatur, dan kod reka bentuk seismik tidak menyediakan garis panduan reka bentuk seismik khusus untuknya. Sebaliknya, gempa bumi yang lalu telah menunjukkan bahawa tiang bertetulang terbina adalah berisiko terhadap beban seismik terutamanya disebabkan oleh ubah bentuk plastik dalam tetulang, keretakan tetulang, lengkokan global tiang, lengkokan tempatan pada web dan bebibir, dan pembentukan plastik engsel pada panel bawahnya. Oleh itu, tingkah laku seismik mereka harus disiasat, dan kaedah pengukuhan yang cekap harus dicadangkan. Dalam kajian ini, kerja eksperimen dan simulasi berangka telah dijalankan untuk menyiasat mod kegagalan yang mengawal tiang bertetulang terbina. Selain itu, kesan ketebalan tetulang, jarak tetulang, jarak kord dan beban paksi ke atas beban muktamad, nisbah kemuluran, kadar degradasi kekakuan dan kapasiti pelesapan tenaga tiang bertetulang terbina telah disiasat melalui pemuatan kitaran separa statik. Kajian ini juga mencadangkan kaedah pengukuhan melalui pengisian grout di dalam kord dan pembalut polimer bertetulang gentian karbon (CFRP) pada kord tiang bertetulang terbina. Kerja-kerja eksperimen termasuk empat tiang yang tidak dikukuhkan dan empat tiang yang diperkukuh dengan jarak tetulang dan jarak kord yang berbeza. Selain itu, 210 tiang bertetulang terbina dengan ketebalan tetulang yang berbeza, jarak tetulang, jarak kord, daya paksi, bilangan lapisan CFRP dan bilangan panel yang diperkukuh telah disimulasikan dalam perisian ABAQUS dan tertakluk kepada beban kitaran. Keputusan yang diperolehi menunjukkan bahawa pembonjolan jaringan kord bersama-sama lekuk tempatan bebibir kord adalah sebab utama kegagalan tiang. Selain itu, tiang bertetulang terbina tidak mencapai kapasiti momen plastiknya kerana lengkokan tempatan dalam bebibir. Tambahan pula, tiang dengan jarak tetulang 62 mm menunjukkan beban muktamad 30% lebih besar daripada tiang dengan jarak tetulang 550 mm. Keputusan juga menunjukkan bahawa tiang dengan jarak tetulang 62 mm mencapai 95.91% daripada kapasiti lenturan teorinya. Ia ditunjukkan bahawa keperluan kod reka bentuk untuk jarak tetulang yang tidak konservatif dan tidak menghasilkan margin keselamatan yang sama untuk kapasiti momen lentur tiang bertetulang terbina. Peningkatan jarak kord daripada 50 mm kepada 150 mm meningkatkan kekuatan sisi lajur sebanyak 35%. Sebaliknya, peningkatan daya paksi daripada 0.1Fy kepada 0.4Fy mengurangkan kekuatan sisi dan anjakan muktamad masing-masing sebanyak 24% dan 36%. Nisbah kemuluran anjakan bagi tiang bertetulang terbina yang tidak teguh adalah kurang daripada dua walaupun tertakluk kepada nisbah mampatan paksi yang lebih kecil daripada 0.2. Keputusan menunjukkan bahawa aplikasi CFRP melambatkan/mengalihkan lekuk tempatan bebibir dan membonjolkan jaringan ke panel atas yang tidak diubahsuai; walau bagaimanapun, peningkatan dalam bilangan lapisan CFRP tidak menunjukkan sebarang kesan yang ketara. Pengubahsuaian tiang menghasilkan peningkatan yang ketara dalam kekuatan sisi dan anjakan yang sepadan masing-masing sebanyak 32.15% dan 39.34%, berbanding tiang yang tidak diubahsuai. Kapasiti pelesapan tenaga tiang yang diubahsuai adalah 66.39% lebih tinggi daripada tiang yang tidak diubahsuai. Tiang yang diubahsuai kehilangan 27%, manakala tiang yang tidak diubahsuai semula kehilangan 52% daripada kekakuan sisinya pada nisbah hanyutan 5.0%. Di samping itu, tiang yang diubahsuai juga dapat mencapai kapasiti momen plastiknya dan memberikan nisbah kemuluran anjakan lebih daripada dua. Hasil kajian ini membantu jurutera latihan untuk memahami tingkah laku seismik tiang berbatang terbina dengan lebih baik dan menyediakan kaedah pengubahsuaian yang cekap untuk tiang ini.

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LIST OF ABBREVIATIONS

AISC	-	American society of steel construction
AFRP	-	Aramid fibre reinforced polymer
ASTM	-	American society of testing of materials
CCFT	-	Circular concrete filled tubes
CFDST	-	Concrete-filled double skin steel tubular
CFS	-	Cold formed steel
CCFST	-	Curved concrete-filled steel tubular trusses
CFST	-	Concrete filled steel tubes
CFRP	-	Carbon fibre reinforced polymer
DCBB	-	Double channel back-to-back
DCFF	-	Double channel face-to-face
DI	-	Double I-sections
EC3	-	Eurocode 3
FEM	-	Finite element method
FRP	-	Fibre reinforced polymer
GFRP	-	Glass fibre reinforced polymer
HRS	-	Hot rolled steel
HSS	-	Hollow structural sections
LTB	-	Lateral torsional buckling
LVDT	-	Linear Variable Differential Transforms
RA	-	Recycled aggregate
RACFT	-	Recycled aggregate concrete filled tube
RC	-	Reinforced concrete
SHS	-	Square hollow sections
SCFST	-	Square concrete filled steel tubes

LIST OF SYMBOLS

A_{ch}	-	Sectional area of chord
A_g	-	Gross cross-sectional area
d	-	Distance between the chords
E	-	Modulus of elasticity
e_o		Bow imperfection
F_y	-	Yield strength
F_u	-	Ultimate strength
F_{cr}	-	Critical buckling stress
F_e	-	Elastic buckling stress
ho	-	Distance between the centroid of Chords
h	-	Web height
I_{eff}	-	Effective moment of inertia
K_m	-	Effective length factor
M	-	Bending moment
M_{Ed}	-	Design value of the maximum moment
M_{pce}	-	Plastic moment capacities
N_{cr}	-	Effective critical force
N_{Ed}	-	Design value of the compression force
P_n	-	Nominal strength
P	-	Axial load
P_{ye}	-	Expected axial yield capacity
R	-	Retrofitted
R_y	-	Ratio of the expected yield stress to the specified minimum yield stress
r	-	Radius of Gyration
r_i	-	minimum radius of gyration
s	-	Centre to centre spacing of battens
S_v	-	Shear stiffness
SG	-	Strain gauge
t_f	-	Flange thickness

t_w	-	Web thickness
μ	-	Ductility ratio
U	-	Un-retrofitted
V	-	Shear force
ν	-	Poisson ratio
w	-	Flange width
δ_u	-	Ultimate displacement
δ_y	-	Yield displacement

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CHAPTER 1

INTRODUCTION

With the existence of life, human beings have always been in search of a safe shelter for their living and safety, for that in the start; they used stones, wood, mud etc., to build a safe place. By the time they started improving their living standard by inventing new construction techniques and materials such as bricks, cement, steel etc. Steel has been used in the construction industry on a vast scale due to its higher strength, durability and ease of fabrication and erection compared to other materials. It is used in constructing high-rise buildings (skyscrapers) and longer span bridges as framed structures almost worldwide. But at the same time, the failure of these structures caused the loss of human life and economy, which may be attributed to the lack of proper design rules, poor quality of material, defective workmanship or a natural disaster such as floods, tsunami or occurrences of frequent Earthquakes.

Among natural disasters, earthquakes have been one of the leading causes of human casualties and property destruction. It is reported that there have been 1.87 million deaths due to earthquakes in the 20th century (1). As a catastrophic event, Earthquake has always been the main concern for civil engineers, despite knowing that we can't eliminate earthquake disasters but with a struggle to save human life as much as possible. Earthquakes may cause structural and non-structural damage during seismic excitations. Structural damages consist of distress induced in structural components of lateral and gravity-load-resisting systems, such as beams, columns, load-bearing walls, and shear walls, as well as horizontal diaphragms, such as slabs and roofs.

There's a saying among seismologists: "Earthquakes don't kill people, Buildings kill people."

Which is true, because seismic damage in structures is caused either by underestimating or avoiding the seismic forces or lack of sufficient strength or lack of inelastic deformability. Lack of strength and/or deformability creates seismically deficient structures that often suffer significant damage during strong earthquakes. Under all such conditions, damage occurs at the critical regions of structures. Properly designed and detailed structures tend to perform in a ductile manner and dissipate seismic-induced energy, reducing vulnerability against earthquake damage, such as columns, which are often responsible for the overall strength and stability of the entire structural system.

The role of columns in the structures is like a backbone in the human body because the stability of the whole structure is dependent on the performance of columns. It is the part of the structure subjected to almost all loadings such as compression, bending, torsion and shear; losing one column can result in partial or complete structural collapse. That is the reason that most of the design standards have introduced the strong column-weak beam concept to ensure that the seismic energy is dissipated through beams and girders rather than the columns. But despite such guidelines, the formation of plastic hinges in columns during a severe earthquake is still unavoidable. The ability of the structure to withstand against earthquakes and to perform adequately in the inelastic range highly depends on the formation of these plastic hinges and their capability to absorb and distribute the seismic energy. Therefore, column performance in the inelastic mode is of utmost importance for the safety of a structure during an earthquake.

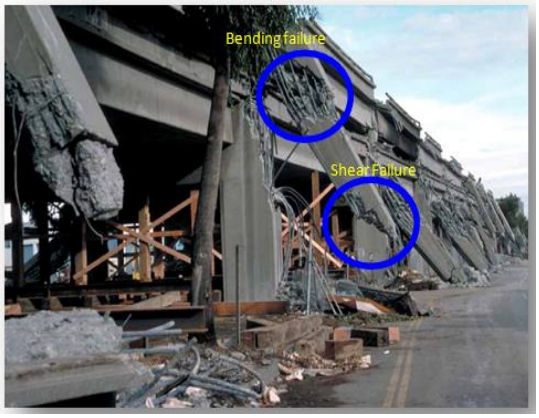
Low seismic resistance of columns is the most likely cause for structures collapse during earthquakes, resulting in significant human and economic loss. The importance of columns can be clearly understood from the damages that occurred in the various structures due to column failures during past earthquakes, as shown in Figure 1.1. Earthquake in Turkey happened on May 1, 2003, at Bingol (see Figure 1.1(a)) resulted in the collapse of many buildings (2), the Canterbury Television

building (see Figure 1.1(b)) in Christchurch, New Zealand, fell after the 2011 Christchurch earthquake killing 115 people due to insufficient seismic design and structural ductility (3). Similarly, the failure of bridge columns in the 1995 Kobe Earthquake and Loma Prieta 1989 earthquake (see Figure 1.1(c-d)) also caused huge loss of life and economy.

(a) Diagonal tension failure in columns, in an Earthquake in Turkey (2)

(b) Shear failure of a column, Christchurch earthquake in New Zealand (3)

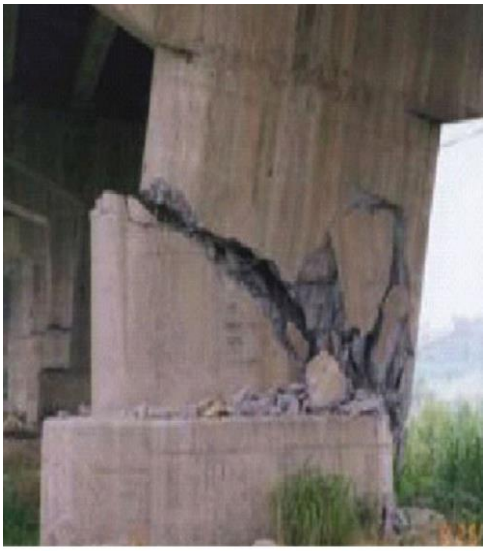
(c) Flexural and Shear failure of an expressway columns 1995 Kobe earthquake (4)



(d) Failure of Cypress viaduct columns Loma prieta 1989 (5)

(e) Building Column Hinging at Base and Top (6)

(f) Collapse of Buildings due to Strong Beam-weak Columns (6)(7)



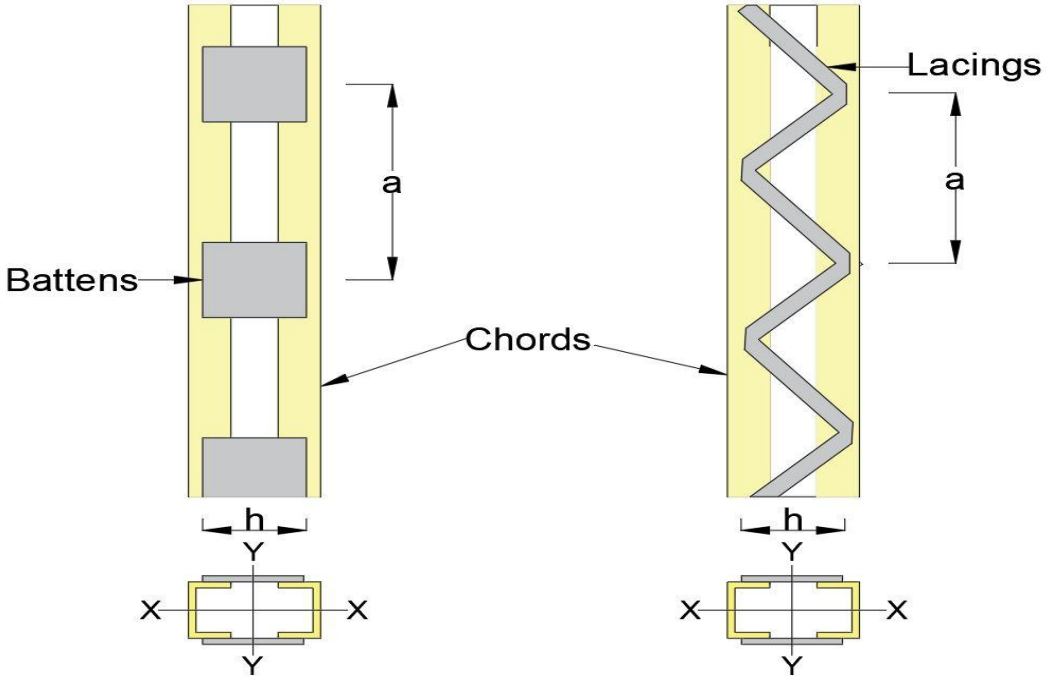
(g) Lack of confinement reinforcement (6)

(h) Shear failure of Bridge Columns (6)

Figure 1.1 Column failure modes

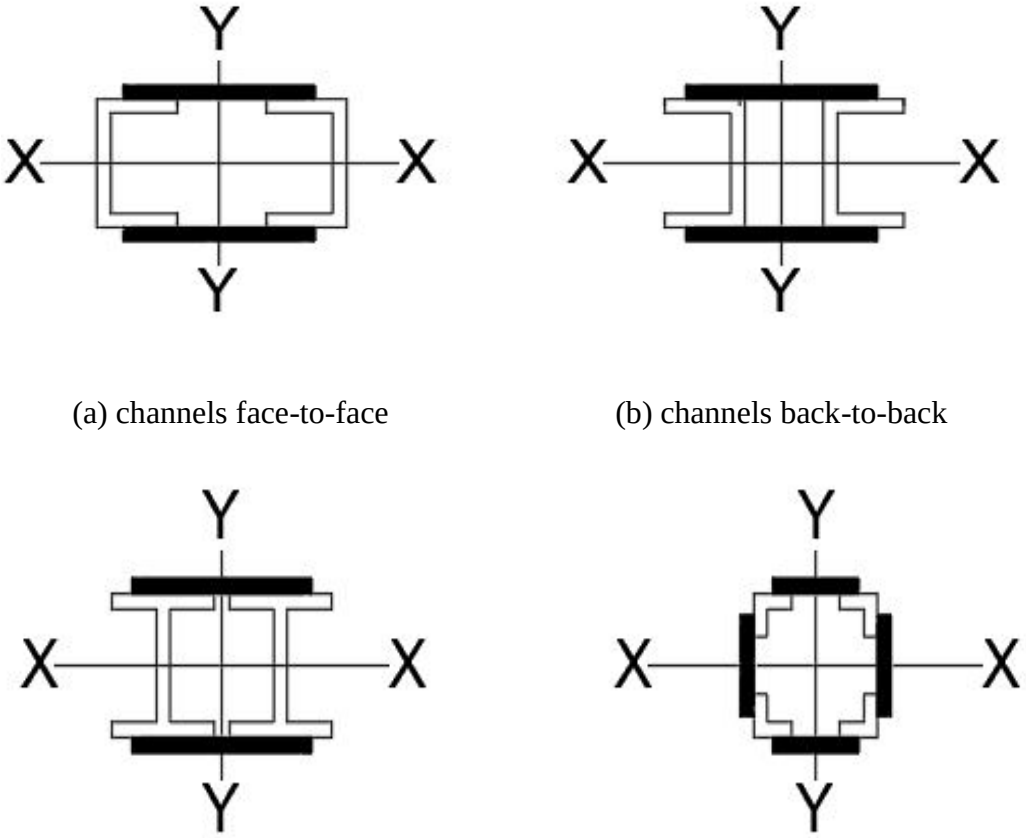
Built-up columns are usually adopted when the single rolled section can't fulfil the desired requirements such as higher axial strength, the moment of inertia, excessive bending and torsional resistance etc. The individual rolled steel sections such as I-sections and C-sections have a larger moment of inertia along the axis perpendicular to the web of sections called the strong axis of sections. The axis parallel to the web is the weak axis of the section. Therefore, the buckling strength of the individual sections is high in the plane of the web and weak in the opposite axis. The' Built-up' section is used to counter such geometrical deficiency of the individual rolled sections. Built-up columns consist of two or more longitudinal sections which are interconnected by transverse members, which hold them to form an integral unit with a continuous longitudinal space between the sections. Depending on the way of connections between the flanges of the sections and the method of force transfer, they are categorised as built-up battened columns and built-up laced columns, as shown in Figure 1.2. These transverse members, such as battens (frame action) or lacing bars (truss action), also act as the shear connection between the longitudinal members to resist the shearing forces. In addition, these transverse connections are also used to reduce the effective length of the main members between the points of transverse connections to prolong the local buckling such that it doesn't occur before the global one. Steel plates or angles are usually used to fabricate battens or laced members. The longitudinal sections of built-up columns are called chords and often made by channel or I-shaped profiles. These longitudinal sections of built-up columns can be of different cross sections and arrangements, as shown in Figure 1.3. The built-up columns mostly failed due to the local buckling of flanges and web of the main chord at the lower panel irrespective of the section's types and arrangements as shown in Figure 1.3. However, the columns composed of I-sections as chord members showed higher lateral strength and potential to reach the Mp of the sections than columns with composed of channel sections (8)(9)(10). Therefore, it is of great interest to determine the governing failure mode of built-up battened columns composed of channels sections considering the effects of batten thickness and spacing, chord distance, and axial force. In addition, an efficient strengthening method is also necessary to counter such excepted failures in built-up battened columns during seismic events.

Similarly, the steel structures are also vulnerable to seismic excitation, as observed during past earthquakes in Bam in December 2003 in Iran, with a loss of 35000 precious life (11)(12)(13). Where the most of the residential and commercial steel buildings constructed using built-up columns were seriously damaged. As a result, different failure modes were observed in the built-up columns, as shown in Figure 1.4. The observed failure mechanisms of built-up columns highlight uncertainties regarding these columns' seismic behaviour.



(a) Battened columns (b) Laced columns

Figure 1.2 Types of built-up (a) battened columns (b) laced columns



(a) channels face-to-face (b) channels back-to-back

(c) I-sections (d) angle sections

Figure 1.3 Types of built-up sections (a) channels face-to-face (b) channels back-to-back (c) I-sections (d) angle section (continue)

1.1 Problem Statement

Columns play a significant role in the stability of structures under gravity and lateral loads. Failure of a column can result in partial or complete collapse of a building. From the history of the past earthquakes, it was found that the built-up battened columns are seismically vulnerable. As shown in Figure 1.4, different types of failure mode, such as plastic deformation of battens, fracture of battens, global buckling of columns, local buckling of web and flanges and formation of plastic hinges at the bottom of built-up columns have been observed for these columns (11,12). Therefore, it is of great interest to determine the governing failure mode of

these columns considering the effects of batten thickness and spacing, chord distance, and axial force.

Plastic deformation of battens

Fracture of battens

Global buckling of columns

Local buckling of column

Figure 1.4 Failure modes of built-up battened columns (11)

Besides, most of the design codes (14–16) do not provide any seismic design specifications for built-up battened columns; consequently, structural design of these columns has been based on equations given for gravity loads. This implies that further investigations are needed to explore the bending capacity, stiffness degradation rate, ductility ratio, and energy dissipation capacity of built-up columns designed in accordance with current design codes. The outcome of such investigations is also important for the seismic analysis of built-up columns. This is mainly due to the fact that so far it is not known these columns should be classified

as force-controlled or deformation-controlled, based on the requirements of ASCE 41-17 (17).

Considering the fact that these columns have often suffered significant damage during past earthquakes, it is also necessary to propose an efficient strengthening method for them that is practical in use by design engineers. It is worth mentioning that still there is no practical method for retrofitting of built-up battened columns against seismic actions. Previous retrofitting strategies have mostly focused on solid/hollow sections (18)(19)(20)(21)(22)(23).

1.2 Research Objectives

The overall focus of this study is to gain a profound insight into the seismic performance of built-up battened columns by considering the various parameters and developing a retrofitting technique. Followings are specific objectives:

(a) To determine the governing failure mode of built-up battened columns under quasi-static cyclic load through experimental works and numerical simulations.

(b) To determine the effect of batten's thickness, batten spacing, and chord distance on the ultimate load, ductility ratio, and energy dissipation capacity of built-up battened columns through experimental works and numerical simulations.

(c) To investigate the effect of axial force on the ultimate load, ductility ratio, and energy dissipation capacity of built-up battened columns through numerical simulations.

(d) To propose a strengthening method for deficient built-up battened columns and examine its efficiency through experimental works and numerical simulations.

1.3 Scope of the study

This study will only concentrate on the built-up battened columns composed of two plain channel sections. The channels will be placed face to face at different distances (i.e., 50 mm, 100 mm and 150 mm) and will be attached through welding with the help of battens with different spacings (i.e., 62 mm, 200 mm, 225 mm, 300 mm, 375 mm, 550 mm and 1200 mm) and thicknesses (i.e., 4 mm, 6 mm and 8 mm). Mild steel channel sections will be used with the yield and ultimate strength of 373 and 508 MPa, respectively. The yield and ultimate strength of the batten's plates will be 388 and 568 MPa, respectively. The column will be subjected to a constant axial force of 10%, 20%, 30% and 40% of their yield load and quasi-static cyclic loading, using FEMA 461 for load protocol. Bending will be considered only around the material free axis of the column. For retrofitting of the section's Sika Grout with the seven days, compressive strength of 25 MPa will be used as infill material, and carbon fibre reinforced polymer (CFRP) used had an elastic modulus of 252 GPa, the ultimate tensile strength of 4900 MPa and an ultimate strain of 2% based on a nominal thickness of 0.164 mm per ply, for external wrapping. This study will be limited to investigating the application of CFRP material only as an external reinforcement, and unidirectional CFRP sheets will be used in this research. Only the lateral effect of the CFRP strengthening technique will be covered in this study; the axial response of the retrofitted section will not be considered. Long term behaviour and environmental impacts of CFRP will also not be covered here.

1.4 Significance of the study

It has been shown during past earthquakes that built-up battened columns have been vulnerable against seismic actions. One main reason to these observations is that seismic design codes do not provide any specifies seismic design guideline for these columns. The outcome of this study will significantly enhance our understanding about the governing failure mode of built-up columns. Besides, since the effect of batten thickness, batten spacing, chord distance and axial force on the seismic behavior of these columns will be investigated, this study can help to prepare

a specific seismic design guidelines for built-up columns. Furthermore, since this study proposes an efficient retrofitting method for the existing built-up columns that are vulnerable against seismic actions, it can enhance the safety of buildings.

1.5 Layout of Thesis

The composition of the thesis is organized into six chapters. Chapter 1 provides background information on the needs and objectives of the current study. Chapters two to six present the literature review, methodology used in the current study, experimental and theoretical studies, numerical study on various aspects and end conclusion of the current research, respectively. Meanwhile, a series of key findings and critical conclusions are summarized at the end of each chapter. Details of these chapters are outlined below.

Chapter 2 presents a review of the existing literature covering topics related to the present study. First, a brief introduction of built-up battened columns is provided, followed by a broad review of its design guide lines in various codes are discussed. These are followed by a review on the shortcomings of the built-up battened columns, with particular attention to the slenderness ratio, shear effect, compound buckling, axial performance and sectional slenderness ratio of the sections on their axial and cyclic performance. Then some previous studies on the cyclic response of built-up battened and laced columns are provided. The static and cyclic behaviour of retrofitted sections such as CFST sections and the sections strengthened with CFRP are then reviewed and compared to highlight the advantages of CFST sections and CFRP wrapping.

Chapter 3 shows the methodology of experimental work used in the current research program for the testing of four conventional hollow sections and four retrofitted built-up battened sections. This study consists of four objectives based on experimental work and numerical simulation. As shown in Figure 1.5, the first, second and fourth objectives involved experimental work and numerical simulation, while the third objective was only based on numerical simulation. The initial step in

the experimental procedure was to identify the quantity and size of test specimens for each objective based on the limitations imposed by laboratory equipment. A total of eight specimens were designed and constructed in a workshop. After the construction of specimens, the next step was to design the test setup and determine the appropriate instrumentation plan for the acquisition of data. Finally, the test specimens were loaded one by one in accordance with the research objectives, and the data was collected for comparison and discussion. Material tests that include tests on the steel, grout and CFRP were also performed to find out the mechanical properties of the employed material.

Chapter 4 first presents the experimental results of four conventional samples tested in the laboratory with different battens spacing and chords distance. Then the results of four retrofitted sections are provided. In both cases, the failure modes of the tested samples were discussed in detail. Next, the performance of all the tested samples was judged in terms of hysteresis loops, backbone curves, stiffness degradation, energy dissipation, strain measurement, displacement ductility ratio, initial and post-yield stiffness. In the end, a comparative study was done between the conventional and retrofitted sections.

Chapter 5 reports the results of numerical analysis obtained using ABAQUS software in the current study. As shown in Figure 1.5, all the four objectives of the current study involve numerical simulation. The first step in the numerical simulation was modelling the parts of the specimen. After modelling, the second step was assigning material properties to each part of the specimen. In the third step, the parts were assembled to form a single specimen, and the interaction between the parts was assigned. The fourth step was the application of loading protocols, boundary conditions and analysis type. The fifth and last step was meshing each part of the specimen. After analysis, the numerical results were validated with the experimental ones. After validation, the parametric study for each objective was conducted, and the data was collected for further analysis and comparison.

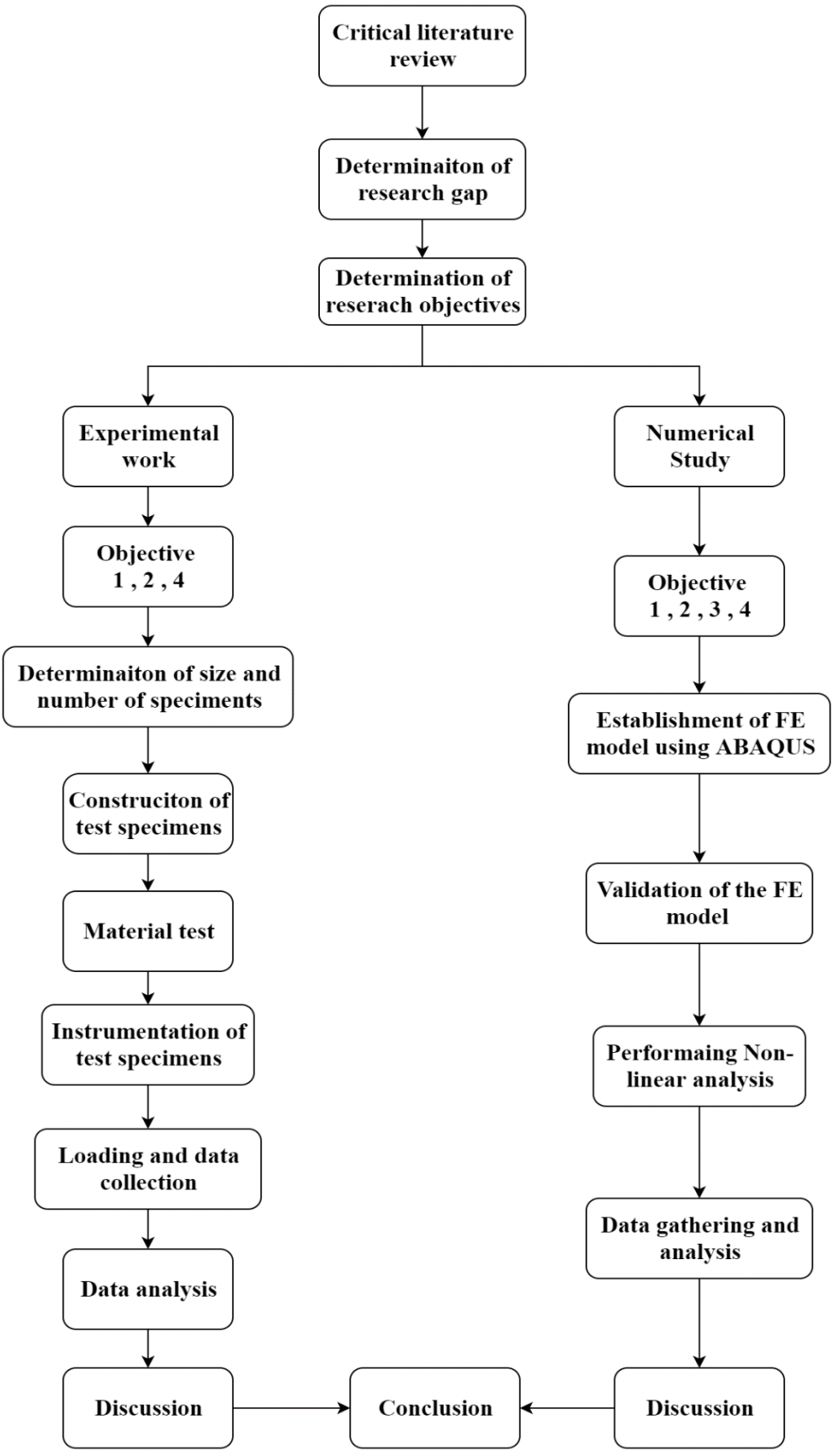


Figure 1.5 Research methodology flow chart

Chapter 6 finally compares and summarizes the findings of this study from experimental work and numerical simulation and highlights the significance of the research project. Suggestions and recommendations for future investigation will be presented.

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