VULNERABILITY ASSESSMENT OF TELECOMMUNICATION STEEL TOWER SUBJECTED TO SEISMIC EXCITATION

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SCHOOL OF CIVIL ENGINEERING
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VULNERABILITY ASSESSMENT OF TELECOMMUNICATION STEEL TOWER SUBJECTED TO SEISMIC EXCITATION

by

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I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

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(Important Note: This form can only be forwarded to examiners for his/her approval after endorsement has been obtained from supervisor)

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ABSTRAK

Menara telekomunikasi telah menjadi jalan utama bagi peradaban moden selama bertahun-tahun kerana mereka adalah bahagian penting dalam komunikasi dan rangkaian pasca bencana yang mesti terus berfungsi setelah gegaran seismik. Walau bagaimanapun, menara dirancang mengikut kesan angin dan bukannya kesan seismik. Sebagai akibat, kesan seismik pada reka bentuk dan pembinaan menara tidak diambil kira. Dalam kajian ini, penilaian kerentanan menara keluli telekomunikasi di bawah semangat gerakan medan dekat dan medan jauh dilakukan. Tujuan kajian ini adalah untuk menilai prestasi seismik menara keluli telekomunikasi menggunakan fungsi kerentanan dan untuk menganggar *Collapse Margin Ratio* (CMR) berdasarkan gerakan tanah medan dekat dan medan jauh. Prosedur analisis dilakukan dalam pelantar dinamik tak linear. Model 2D dirancang berdasarkan ASTM A 992 / A 992M untuk anggota rangka keluli, yang merangkumi rasuk, tiang dan rembat. Engsel plastik ditugaskan pada anggota bingkai. *Nonlinear Time History Analysis* (NL-THA), *Incremental Dynamic Analysis* (IDA), analisis kerapuhan dan CMR dilakukan untuk menilai prestasi seismik menara di bawah dorongan gerakan tanah dengan menggunakan perisian ETABS 18. Lengkung IDA dikembangkan dan kemudian digunakan untuk menghasilkan lengkung kerapuhan. 18 set gerakan tanah medan dekat dan medan jauh, digunakan dalam analisis berdasarkan pangkalan data gerakan tanah kuat PEER dan COSMOS. Keluk IDA dibandingkan berdasarkan tiga tahap prestasi, iaitu *Immediate Occupancy* (IO), *Life Safety* (LS) and *Collapse Prevention* (CP) dengan merujuk kepada FEMA 356. Hasil dari lengkung IDA, lengkung kerapuhan dan CMR yang dikira menunjukkan bahawa prestasi seismik menara yang dikenakan gerakan tanah medan jauh lebih baik daripada gerakan tanah medan dekat. Dalam hal ini menunjukkan bahawa kerentanan seismik menara lebih besar dalam gerakan tanah medan dekat daripada gerakan tanah medan jauh. Sebagai akibat,

gerakan tanah medan dekat lebih merosakkan dan berbahaya bagi menara, yang menyebabkan kerosakan atau runtuhnya menara.

ABSTRACT

The telecommunication towers have become a key lifeline for modern civilizations over the years since they are critical parts of communication and post-disaster networks that must continue functional after a seismic excitation. However, the towers were designed according to wind effects rather than seismic effects. As a result, the effect of the seismic on tower design and construction was not taken into account. In this study, the vulnerability assessment of the telecommunication steel tower under near-field and far-field ground motions excitations was carried out. The aim of this study is to evaluate the seismic performance of a telecommunication steel tower using vulnerability functions and to estimate the Collapse Margin Ratio (CMR) based on the near-field and far-field ground motions. The analysis procedures were carried out in a nonlinear dynamic platform. The 2D model was designed based on ASTM A 992/A 992M for steel frame members, which include beams, columns and bracings. The plastic hinges were assigned to the frame members. Nonlinear Time History Analysis (NL-THA), Incremental Dynamic Analysis (IDA), fragility analysis and CMR are performed to evaluate the seismic performance of the tower subjected to ground motions excitations by using ETABS 18 software. The IDA curves are developed and then used to generate the fragility curves. 18 sets of near-field and far-field ground motions, respectively, are used in the analyses based on the PEER and COSMOS strong ground motions database. The IDA curves are compared based on three performance levels, which is Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) by referring to the FEMA 356. The results from the IDA curves, fragility curves and the calculated CMR indicated that the seismic performance of the tower subjected to the far-field ground motion was better than the near-field ground motion. This reveals that the seismic vulnerability of the tower was greater in near-field ground motion than in the far-field

ground motion. As a result, the near-field ground motion is more damaging and destructive to the tower, leading to failure or collapse of the tower.

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ASTM	American Society for Testing and Materials
CMR	Collapse Margin Ratio
COSMOS	Strong-Motion Observation System
CP	Collapse Prevention
FE	Finite Element
FEMA	Federal Emergency Management Agency
IDA	Incremental Dynamic Analysis
IO	Immediate Occupancy
LS	Life Safety
MCE	Maximum Considered Earthquake
NL-THA	Nonlinear Time History Analysis
PEER	Pacific Earthquake Engineering Research
PGA	Peak Ground Acceleration
SDR	Storey Drift Ratio
UBC	Uniform Building Code

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Telecommunication steel tower is typically designed considering wind effects as the primary source of the lateral loads with no attention given to seismic effects. Earthquake effects on towers may be more severe than wind effects and should be considered as a design check, at least in a simplified form (Khedr and McClure, 2000). In order to do so, a vulnerability assessment of telecommunication steel tower that has been subjected to seismic excitation must be considered.

Furthermore, there are a few articles on the seismic performance of transmission steel towers in literature (Zhang *et al*., 2020; Zhao *et al.*, 2020; Barrera, 2021) . Several codes, standards and design provisions have proposed simplified static methods for the seismic estimation for telecommunication steel towers (Assi, 2006; Ismail, 2016), but none of them has suggested using dynamic or the Nonlinear Time History Analysis (NL-THA). This provision demonstrates that their gap and limitations are unsuitable for estimating seismic design capability. As a result, the collapse of tower can be avoided by ensuring better seismic code compliance of new constructions and rehabilitating existing structures. Besides that, since the transmission lines spans are large in comparison to today's civil engineering construction, the effects of multiple excitations must be carefully considered, and the frequent failure of transmission line tower systems shows that the load pattern defined in the codes still does not accurately reflect severe load conditions (Albayrak and Morshid, 2020).

This study also looks at the far-field and near-field ground motions. The two properties of near-field ground motion are a long-period pulse in the acceleration time history and a high peak velocity. The far-field ground motion is less unfavourable and damaging compared with near-field ground motion (Tian *et al.*, 2017). Zhang and Iwan (2002) demonstrated that a structure's dynamic reaction to near-field ground motion can be twice that of the identical far-field ground motion. This is due to the high peak velocity of the near-field ground motions. Yahyai et al. (2011) evaluated the impact of near-field ground motions with forward directivity on telecommunication towers, and the results show that the drift ratio and the maximum displacement are significantly increased, causing a huge displacement in the tower when the proportion of the structure period to near-field pulse period is reduced and approaches to 1.0. To date, only a little amount of study has been done to evaluate the vulnerability assessment of the telecommunication steel tower under the far-field and near-field ground motions excitation. Finally, the seismic vulnerability assessment of the tower under far-field and near-field ground motions excitation must be performed.

1.2 Problem Statement

Earthquakes have damaged a lot of infrastructures such as transmission towers, bridges and telecommunication towers. However, the telecommunication steel tower is chosen to be studied, which will be subjected to seismic excitation. Telecommunication steel tower as stated earlier is mainly designed considering the wind effects rather than the seismic effects as the primary sole of the lateral load. This is because wind effects are more domain than the seismic effects in the design of the tall telecommunication steel tower especially at the open surface area where the wind lateral load is much greater than the seismic lateral load. However, the seismic lateral load cannot be denied because the seismic lateral loads can also give a huge damage to the telecommunication steel tower especially at the high-seismic zone where repeated earthquakes can occur. Furthermore, very few articles have carried out the telecommunication towers subjected to seismic excitations compared to the transmission towers (Veena *et al*., 2017; Azeem *et al.*, 2018; Gunathilaka *et al.*, 2018). In this study, a nonlinear dynamic analysis is performed including the Nonlinear Time History Analysis (NL-THA) and Incremental Dynamic Analysis (IDA) due to the seismic is a type of dynamic loading. In addition, the beams, columns and bracings of the telecommunication steel tower are assigned plastic hinges.

Moreover, fragility curves, which are conditional probability statements of vulnerability of a telecommunication steel tower as a function of ground motion intensity, have become a typical technique to make these seismic evaluations. Telecommunication steel tower fragility curves, that represent the likelihood of a tower achieving a specific damage state for a particular ground motion variable, are critical in determining the overall seismic vulnerability assessment of a tower.

Furthermore, the Collapse Margin Ratio (CMR), originally proposed in FEMA P695, is one of the best structural collapse indicators established in the last decade (Kassem *et al.*, 2020). According to FEMA P695, various factors influence the CMR, including ground motion variability and uncertainty in the structure's design, analysis, and construction. These variables are combined in a collapse fragility curve, which describes the likelihood of the seismic-force-resisting system collapsing as a function of ground motion intensity (FEMA, 2009). As a result, in the investigation of the structural seismic collapse prevention, the CMR is the most effective tool for determining the capability to withstand structural collapse.

Far-field and near-field earthquakes are two main types of earthquakes that have different characteristics and involve different behaviours in structures (Patil *et al.*, 2016). Near-field earthquakes occur in fields close to the fault, while far-field earthquakes occur in fields far from the fault. As a result, some researchers propose a near-field range of 10 to 60 km around the fault (Heydari and Mousavi, 2015). For instance, The UBC97 code defines a distance of less than 15 km from the earthquake epicentre as the near-field range in determining a definite range as the near field of the fault (International Conference of Building Officials, 1997). As a result, the distance for the near-field range is less than 15 km from the epicentre of an earthquake while the far-field range can be described as a distance greater than 15 km from the epicentre of an earthquake.

The properties of far-field ground motions vary from near-field ground motions. Near-field ground motions have a higher acceleration and a restrictive frequency range when compared to higher frequencies of far-field ground motions (Heydari and Mousavi, 2015). Furthermore, far-field ground motion is less disruptive and devastating than near-field ground motion (Tian *et al.*, 2017). This may show that far-fault ground motions are less likely to cause telecommunication steel tower failure or even collapse than near-field ground motions. Hence, it is critical to evaluate the vulnerability of a telecommunication steel towers that subjected to the far-field and near-field ground motions, as well as to increase the seismic capability of these structures, in order to reduce the risk of tower failure or collapse during an earthquake and keep the tower operational after the event.

As a result, this study proposed to provide the designer with the appropriate method for evaluating towers using single earthquake which include far-field and near-field ground motions, in order to estimate the Collapse Margin Ratio (CMR) and the probability of damages using vulnerability functions. From this study, the telecommunication steel tower will be able to design and withstand seismic excitations, which will be useful in updating the code regulations and demonstrating that avoiding and ignoring seismic provisions is not an appropriate idea.

1.3 Objectives

The main objectives of this study are:

1. To evaluate the seismic performance of a telecommunication steel tower using vulnerability functions

2. To estimate the Collapse Margin Ratio (CMR) based on the far-field and near-field ground motions

1.4 Scope of Work

A study of vulnerability assessment of the telecommunication steel tower consisting of a simple 2D frame structure under far-field and near-field ground motions. The telecommunication steel tower structural configuration based on the gravity and seismic loadings such as peak legs, cage bracings, cage legs, cross arms, primary bracings, leg bracings and main legs are designed. After that, the materials properties such as shear modulus, Poisson's ratio, modulus of elasticity, and steel grade are defined according to the ASTM A 992/A 992M. The type of frame section used in this design is steel equal angle. The base connection is assigned to the fixed connection.

Before the seismic analysis, the hinges are defined and assigned to each of the frame members. The PEER and COSMOS strong ground motions database were used to extract 18 sets of far-field and near-field ground motions, respectively, in this study. Then, the set of extracted ground motion records with different PGAs are applied in order to assure all the possible scenarios by using ETABS software.

Every ground motion data is linearly scaled to have various PGAs ranging from 0.1g to PGA that corresponds to structural collapse with a 0.1g increment for the dynamic analysis. The nonlinear dynamic time history will carry out until the 2.0% maximum SDR according to the CP structural performance level (S-5) that stated in the FEMA 356 (FEMA, 2000). After that, Incremental Dynamic Analysis (IDA) is performed in terms of maximum SDR and PGA accompanied with three performance limit states which are

Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The vulnerability of the telecommunication steel tower is then determined using a fragility curve based on the three performance limit states. In addition, the CMR is estimated at the CP stage. Finally, the plastic hinges are assigned on the frame members, which include beams, columns and bracings, where the members act on the axial forces only.

1.5 Layout of Dissertation

This study consists of a total of 5 chapters which are introduction, literature review, methodology, results and discussion, as well as conclusion. Chapter 1 of this study discussed the background of study, problem statement, objectives, scope of work and dissertation of work.

Chapter 2 is the literature review which discusses the related review or research articles done by previous researches such as telecommunication steel tower, far-field and near-field ground motions, Nonlinear Time History Analysis (NL-THA), Incremental Dynamic Analysis (IDA), fragility analysis as well as Collapse Margin Ratio (CMR).

Chapter 3 is relating to the methodology of this study, which describes the overall flow method and general modelling and software analysis procedures such as the NL-THA and assigning the plastic hinges to the frame members using ETABS software. After that, IDA, fragility analysis and CMR are performed.

Chapter 4 refers to the results and discussion of this study which will cover the results obtained from the analyses. The results obtained will be thoroughly discussed based on the vulnerability functions.

Chapter 5 is the conclusion of this study which concludes the overall achievement of this result based on the objectives. The contribution of this study to civil engineering will be discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this Chapter 2, past researches undertaken by other researchers that are related to this thesis subject will be more focused. An overview of the repeated earthquake sequences across the world will be reviewed in this chapter. Furthermore, the various analyses that will be used to evaluate the vulnerability assessment of the telecommunication steel tower under far-field and near-field ground motions will be discussed in this chapter.

2.2 Telecommunication Steel Tower

A 7.0 magnitude earthquake struck near Port au Prince, Haiti, on January 12, 2010. As a result, the communication infrastructure was severely damaged, causing the public telephone system to be unavailable. Digicel is Haiti's largest cellular provider, and its network has been weakened. Although it was operational by 14 January 2010, the volume of calls exceeded its capability, and most calls could not be linked. The Comcel Haiti facilities, on the other hand, were not seriously affected. Its mobile phone service was temporarily suspended on 12 January 2020, but 70% of it was restored after two days (Bendimerad, 2013). This event highlighted the importance the communication infrastructures need to be stabilized during seismic events to be rolled as an emergency response that can be sent from authorities to citizens as well as provide the communication services during the earthquake event.

Figure 2.1:Damaged Communication Infrastructures (Bendimerad, 2013)

Tian et al. (2020) proposed the collapse simulations of the communication tower subjected to wind load were analyzed with different wind attack angles using the IDA method based on the dynamic explicit method. The FE model of a 60 m tall communication tower is built in ABAQUS (version 6.10) software. In addition, the collapse fragility analysis of the tower was looked into, as well as the effect of the wind attack angle.

Fernández Lorenzo et al. (2020) used static equivalent and dynamic time history methods to compare the structural response of a self-supported communication tower in terms of internal forces and displacements under hurricane wind conditions. Gust Response Factor (GRF) with the formulation proposed in EC3: Part 3-1 was the static equivalent method used in this analysis. In SAP2000 software, a FE model of a 60 m high lattice tower with a square in-plane cross-section is built under design wind loads.

Rezayibana (2020) studied the effect of soil type on seismic response of the stiff and ductile part of tall telecommunication towers with random vibration analysis. In the modeling and analysis, various conditions of the soil under the tower and various damping are used. ABAQUS software was used to build a FE model of the Milad tower. The analysis was done using the Pseudo-Excitation Method because of the large number of elements of the FE model.

Tsavdaridis et al. (2020) proposed using structural topology optimization to develop a better solution for lattice self-supported telecommunication towers in terms of weight-to-stiffness ratio. The structural behavior of the optimized tower models was demonstrated through comparative modal analyses. Furthermore, a research-led design was used to improve the optimized lattice tower's geometric cross-sectional characteristics, which were then exposed to quasi-static analysis and regression analysis. Model files for the 19 m tall OT and UA towers were moved to the structural software system Oasys GSA from the AutoCAD software as shown in Figure 2.2, and steel framework members were assigned to each. Furthermore, due to a restriction in the software package STAAD Pro V8i SS6, all components of both towers are stimulated as 'space' components.

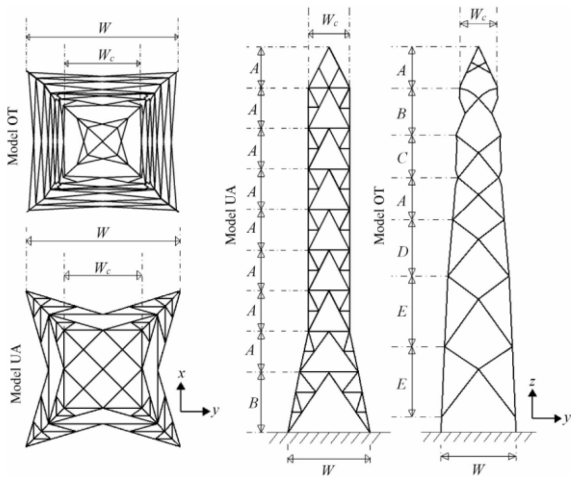

Figure 2.2: General Configuration of Model OT and UA in Plan and Elevation (Tsavdaridis *et al.*, 2020)

Aslani et al. (2019) suggested an optimal analytical approach for calculating the quantity of direct lightning strokes to tall towers when a telecommunication tower is chosen. The lightning leader advancement is evaluated for all lightning leader tip positions in the space above the tower and for all possible lightning current levels in the standard numerical method. Moreover, the lightning performance in terms of the computation time and the quantity of direct lightning strokes with various parameters is determined by applying the original imperialist competitive algorithm. The simulation results were evaluated by comparing to the impulse testing performed on a built model in a high voltage laboratory to see how effective the results were.

Ribeiro et al. (2019) used a constant monitoring system to evaluate dynamic impact of induced wind on a high-rise Monte da Virgem telecommunications tower based on the. An ambient vibration test was conducted as well as the continuous measurements of accelerations, wind speed and direction using a constant monitoring system installed in the 177 m tall tower, were done over the 6 month experiment campaign. The enhanced frequency domain decomposition method (EFDD) with ARTEMIS software was used to identify the modal parameters in the ambient vibration test. On the other hand, the constant monitoring system contains piezoelectric anemometers, accelerometers, and a meteorological station.

Chandra and Sengupta (2019) presented a comparative study using dynamic analysis of self-supporting telecommunication tower for optimum modal combination and discretization. The structures that do not have a lumped mass system are thought of as a continuous system that is further idealized into a set of small elemental segments. In addition, structural analysis of these elemental segments is being carried out using the FE Method. The response spectrum analysis of a telecommunication tower under ground vibration is carried out using STAAD Pro V8i software. The ground vibration is considered a random vibration that can be analyzed using a probabilistic method in the seismic analysis.

Szafran et al. (2019) used tensioned joint reliability to estimate the reliability of slender steel lattice telecommunication towers. A full-scaled pushover test of a 40 m tall lattice tower was used as the starting point for further analyses in this experiment. For the random wind loads, a computational investigation was carried out. Furthermore, a full-time stochastic finite element method (SFEM) dynamic analysis with respect to the particular wind velocity-time function, shell FE stimulation of two specific tower joints, and elastic-plastic range determination of joint reliability using the first-order and second-order reliability methods were all considered numerically.

Thakur et al. (2019) studied the influence of rooftop telecommunication tower on set back-step back buildings resting on different ground slopes. A response spectrum analysis was conducted and compared on the 4 legged angled section telecommunication tower under seismic loading according to IS 1893:2002 in zone IV with PGA 0.24 g by changing tower positions with the current host structure built up on ground at 20° and 30° slopes in both X and Y directions. The open frame function of SAP2000 software was used to create the building, which stimulates the 3D space frame.

Gao and Wang (2018) performed the progressive collapse analysis of lattice telecommunication towers under wind loads. An alternate load path approach was used to do a nonlinear dynamic analysis on a 50 m tall typical standard latticed tripole and angle towers, respectively. A progressive collapse fragile curve and a dynamic sensitivity index based on the collapse probability of both towers under wind loads are proposed to identify the most undesirable wind path for both towers and to evaluate the anti-collapse performance of the both towers respectively. ABAQUS software was used to build both 3D nonlinear FE models of the prototype towers.

Tessari et al. (2017) proposed applying the Performance-based Wind Engineering methodology to the probabilistic analysis of latticed telecommunication towers, evaluating various calculation models for wind force estimation on this type of structure. A telecommunication tower reliability assessment was also carried out. In this study, two separate models were used to assess the wind motion on latticed telecommunication towers: a static and a dynamic model.

Szafran (2015) studied the plastic deformation, failure mode and failure mechanism of a full-scale 40 m high lattice telecommunication tower during a pushover test. A comparison of the standard buckling resistance and tower legs' axial compression forces have been proposed. The load cell and electric resistance strain gauges installed on the triangular-sectioned tower components were connected to specialized computer software that correlated the data.

Hariri-Ardebili et al. (2014) used the endurance time analysis (ETA) method to evaluate the seismic stability of a 435 m tall Tehran telecommunication concrete tower, contrasting it to the time history analysis and IDA methods. The tower is analyzed under single ground motion. OpenSees software is used to create a 2D nonlinear model of the tower, which includes the head structure, shaft and transition.

2.3 Far-field and Near-field Ground Motions

Single and repeated earthquakes are the two types of earthquakes that can occur. However, this study is focused on a single earthquake. Near-fault and far-fault ground motions are introduced in a single earthquake.

Kamgar et al. (2020) studied the Nagasaki airport tower, which has been modelled as a single-degree-of-freedom (SDOF) system with the effect of soil-structure interaction taken into account using a modified tuned liquid damper (MTLD). An approximation cone method based on semi-infinite boundary conditions is used to model the soil effect. Furthermore, six real near-fault ground motions are selected to study the seismic behaviour of the MTLD system. Chandler's classification was used to select these earthquakes (Gholizadeh and Salajegheh, 2010). Gray Wolf Optimization (GWO) approach is used to calculate the optimum parameters of the MTLD system.

Habieb et al. (2019) evaluated the base isolation effectiveness for the seismic performance of a historical mansory bell tower using three types of commercial isolators which are High Damping Rubber Bearing (HDRB), Lead Rubber Bearing (LRB) and Friction Pendulum System (FPS) Isolator. Each individual isolator was modeled using a representative Abaqus User Element (UEL) for the global seismic analysis of the isolated masonry bell tower. Nonlinear dynamic analyses with near-fault El Centro ground motions and far-fault Mirandola ground motion were used to analyze the seismic response of the tower in various configurations, including base isolated and fixed-base.

Tian et al. (2017) stimulated the collapse of a high-fidelity 3D FE model of a long span transmission tower-line system subjected to near-field ground motions. The distance for the near-field ground motion is less than 20 km. The IDA used 20 near-field ground motions available from the PEER database to investigate the collapse seismic fragility, damage positions, CMR and dynamic robustness of transmission towers. In this analysis, the ABAQUS software is used to create a 3D FE model of the long span transmission tower-line system. This study can be used as a benchmark for large-span transmission tower-line systems that are subjected to near-field ground motions.

Mo et al. (2017) studied a monopile offshore wind turbine under various operating conditions using the seismic fragility analysis. The likelihood of exceeding various damage states was determined using fragility curves. Moreover, to achieve the seismic responses and EDPs, a nonlinear time history truncated incremental dynamic analysis (TIDA) was performed. The nonlinear dynamic analysis used 24 earthquake motion records from the PEER database as input ground motions, including 9 far-field and 15 near-field ground motions records. OpenSees platform is used to construct a FE model for a 5MW monopile offshore wind turbine.

Patil et al. (2016) evaluated the structural performance of a parked wind turbine tower subjected to strong ground motions. ANSYS software is used to develop a detailed FE model of 80 m tall VESTAS 1.65 MW wind turbine tower. The seismic fragility analysis was performed to study the seismic response and performance of the tower subjected to ground motion excitation. The wind turbine tower is subjected to 15 near-field and 17 far-field ground motions available from the PEER strong ground motion database in this study.

Hasan et al. (2011) evaluated the effects of various seismic excitations on the response of multi articulated offshore towers, with a particular focus on the impact of the vertical component of ground motions on the nonlinear dynamic response of such towers with distributed lumped masses along the shafts. The offshore is modelled as an "inverted pendulum" with lower and upper latticed shafts linked by two rotational springs, resulting in a two degree of freedom model for hydrodynamic force calculations. This study takes into account six different collections of actual ground motion data, including near-fault and far-fault records. The "nearby-fault" record has a range of $R_f < 15$ km, as defined by UBC97 (International Conference of Building Officials, 1997). The records were chosen according to the following requirements:

1) moment magnitude $M_w > 6.0$, and
2) the closest distance to fault rupture

Yahyai et al. (2011) investigated the impact of near-fault ground motions induced by forward directivity on the telecommunication towers, which can release a large amount of energy in a short period of time. Nonlinear dynamic analysis is conducted using three near-fault earthquake records with forward directivity and nine simulated pulses, which are used to a 3D FE model of the Milad Tower. The near-fault distances are assumed to be 5, 10, 15 km from site location since the distance from the fault ranges between 5 and 20 km. ABAQUS behavior models are used to analyze the nonlinear behaviour of materials which are steel and concrete.

2.4 Vulnerability Assessment

The effects of earthquakes on telecommunication steel tower should not be underestimated in relation to wind effects, since earthquakes can cause extensive damages to the telecommunication steel tower, making the services such as telephoning, television or wireless internet inoperable. As a result, a multi-analysis approach to seismic vulnerability assessment of telecommunication steel tower subjected to seismic excitation is needed.

2.4.1 Nonlinear Dynamic Analysis

Tian et al. (2019) proposed a novel shape memory alloy-tuned mass damper for the seismic vibration control issue of power transmission tower. The control effect of using different shape memory alloy-tuned mass dampers is analyzed using Nonlinear Time History Analysis (NL-THA). ANSYS software is used to create the 3D finite model of a power transmission tower.

Alminhana et al. (2018) developed a special-purpose nonlinear dynamic analysis technique for the modelling of multi-span line sections under progressive failure scenarios. This technique uses a central finite difference scheme modified for a non-constant time increment to perform time-domain analysis and verify the full-scale test results for a single lattice tower and a line section with seven towers.

Tian and Gai (2016) studied the nonlinear seismic behaviors of various boundary conditions of transmission tower-line system under nonuniform seismic excitations. Suspension and tension transmission towers are the two types of transmission towers, and the responses of these two types of transmission towers are analyzed using the time history analysis method, respectively. The 3D FE tower-line systems are built using SAP2000 software.

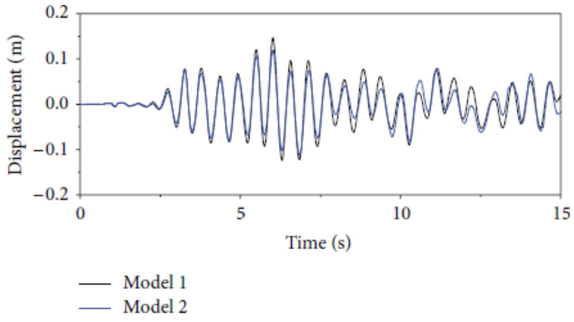

Figure 2.3: Displacement Nonlinear Time History (Tian and Gai, 2016)

The concept of Incremental Dynamic Analysis (IDA) method has been proposed by Bertero as early as 1977 and becomes a valuable tool to evaluate the structure performance and capacity under seismic loading (Vamvatsikos and Allin Cornell, 2002). Tian et al. (2020) focused on the fragility and collapse assessments of a typical long span transmission tower-line system under wind loads. The ultimate capacity and the collapse mechanism of the structure are determined using the IDA process. Due to the uncertainty of wind loads, a fragility analysis for assessing anti-collapse efficiency is also carried out. Based on engineering data, ABAQUS software is used to create a comprehensive FE model of the system.

Pan et al. (2020) numerically determined the sensitivities of a transmission tower's seismic reactions and seismic fragility estimations to various sources of uncertainty, including ground motion and structural uncertainties. The IDA method is used to create probabilistic seismic demand model (PSDM), which are then used to establish fragility curves, and the Latin hypercube sampling methodology is used to construct uncertain models with various levels of uncertainty. ABAQUS (version 6.12) software is used to create a thorough FE of the transmission tower.

Tian et al. (2019) used the PSDM to study the seismic fragility of the transmission tower under the near-field ground motions excitation in terms of the spectral acceleration and the maximum inter-segment drift ratio (ISDR) at the fundamental period of the structure. The PSDM data is obtained using the IDA method, and a pushover analysis is also performed to determine the capacity limit state for the tower, which includes serviceability, damage control and collapse prevention. Furthermore, a fragility curve is established to evaluate the vulnerability of a typical tower. ABAQUS (version 6.12) software is used to construct the FE model of the transmission tower.

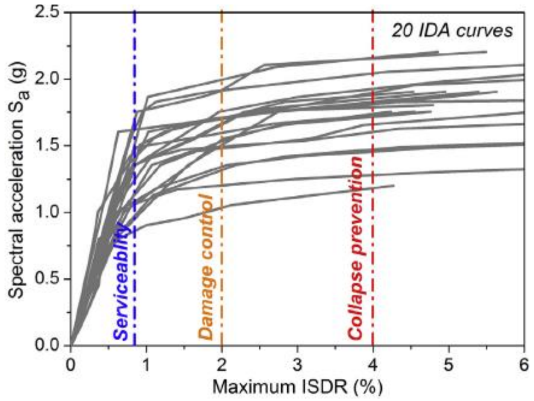

Figure 2.4: 20 Seismic Records using IDA (Tian *et al.*, 2019)

Tian et al., (2019) simulated the collapse of a long span transmission tower-line system while considering the member buckling effect by using the Marshall model, which can capture the nonlinear behavior of the steel pipe. An IDA method was used to assess the collapse-resistant capacity of the transmission tower, and the collapse mechanism of the long span transmission tower-line system was investigated under various wind attack angles. ABAQUS software is used to construct the 3D FE model of the long span transmission tower-line system.

Li et al. (2018) developed a probabilistic assessment method for a typical transmission tower-line system subjected to high wind loads during synoptic winds. An IDA method is carried out in the time domain to assess the performance of the global transmission tower-line system and to obtain the capacity curve. The transmission tower-line system is numerically modeled using ANSYS software.

2.4.2 Fragility Analysis

Seismic fragility analysis is a valuable method for evaluating the seismic performance of a structure. Furthermore, the fragility analysis is often used to analyze the vulnerability of towers that are prone to ground vibrations, according to the previous IDA experts.

Fu et al. (2020) studied a process of developing the fragility surface of a transmission tower under combined wind speed and rain loads, and suggested an alternative intensity measure dependent on the wind speed and rain intensity to meet the requirement of fragility analysis with two intensity measures. ANSYS software is used to build a FE model of the transmission tower-line system. The conditional probability of a transmission tower achieving the damage limit state under a given IM can be developed by assuming that the EDP at a given IM correlates with the lognormal probabilistic distribution as shown in Equation 2.1.

$$P[EDP \geq LS|IM] = \Phi\left(\frac{ln(EDP) - ln(LS)}{\beta_{EDP|IM}}\right) \quad (2.1)$$

where $\Phi(\cdot)$ is the standard normal distribution function; $\beta_{EDP|IM}$ is the EDP's lognormal standard deviation.

Xue et al. (2020) studied the effect of transmission tower-line contact on the bulk power system during hurricane. Fragility analysis is carried out for the transmission tower-line system which takes into account tower-line interaction. However, improving the computational efficiency of the fragility analysis of the transmission tower-line system is crucial, as the dynamic response of the transmission tower-line system is complex and computationally demanding. ANSYS LS-DYNA software is used to analyze the FE model of the transmission tower-line system. The damage and failure probability $F_R(V)$ is calculated in structural wind fragility analysis as shown in Equation 2.2 for a given wind speed V.

$$F_R(V) = P[l \geq LS|\bar{V}_{10} = V] \tag{2.2}$$

where LS is limit state; l is the stimulated response compared with the LS; l is the top displacement of the middle tower in the study in the development of the transmission-line network fragility curve; $\overline{V}_{10}$ is the mean wind speed at 10 m varying from 15 m/s to 70 m/s with 5 m/s increase.

Long et al. (2018) presented a generalized finite particle approach framework for transmission tower collapse simulations due to unidirectional earthquake ground motions. ANSYS and MATLAB software are used for the 3D FE model and the 3D finite particle model of the tower respectively. The finite particle method can be used to perform a collapse seismic fragility analysis. The collapse seismic fragility analysis is based on 12 earthquake ground motion recordings from the PEER database. The structural collapse seismic fragility analysis is described as the conditional probability of the structure collapsing under a particular PGA can be shown in Equation 2.3.

$$P_f = \Phi\left(\frac{ln\,PGA \; - \hat{\mu}_{ln\,PGA|Collapse}}{\hat{\sigma}_{ln\,PGA|Collapse}}\right) \tag{2.3}$$

where $\Phi(\cdot)$ is the standard normal distribution function; $\hat{\mu}_{\ln PGA|Collapse}$ and $\hat{\sigma}_{\ln PGA|Collapse}$ are the mean and standard deviation of ln PGA_i for structural collapse, respectively, which can be determined as follows:

$$\hat{\mu}_{ln\,PGA|Collapse} = \; ln\left(\frac{\hat{\mu}_{PGA|Collapse}}{\sqrt{\delta^2 + 1}}\right) \tag{2.4}$$

$$\hat{\mu}_{ln\,PGA|Collapse} = ln\left(\frac{\hat{\mu}_{PGA|Collapse}}{\sqrt{\delta^2+1}}\right) \tag{2.4}$$

$$\hat{\sigma}_{ln\,PGA|Collapse} = \sqrt{ln(\delta^2+1)} \tag{2.5}$$

$$\delta = \frac{\hat{\sigma}_{PGA|Collapse}}{\hat{\mu}_{PGA|Collapse}} \tag{2.6}$$

$$\hat{\sigma}_{ln\,PGA|Collapse} = \frac{1}{n-1}\sum_{i=1}^{n}\left(PGA_i - \hat{\mu}_{PGA|Collapse}\right)^2 \tag{2.7}$$

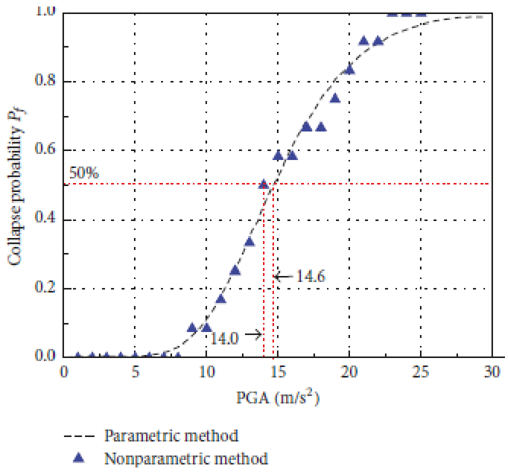

Figure 2.5: Collapse Seismic Fragility Curves (Long *et al.* , 2018)

Katsanos et al. (2017) used nonlinear time-domain analysis to analyze the multi-hazard response analysis of a modern 5MW offshore wind turbine. The multi-hazards environment includes the wind, wave and earthquake. A completely integrated model of the offshore structure was established by using HAWC2, an aeroelastic algorithm that incorporates the interaction between the inertia and elastic forces formed in the structure, as well as the induced hydrodynamic and aerodynamic forces. The analysis is based on 40 sets of ground motions from the PEER-NGA database. Furthermore, fragility analysis of the offshore wind turbine is carried out. Based on the structural reliability theory, fragility is defined as the likelihood of structural demand (D) approaching or exceeding a specific capacity limit (C) for a particular IM of the hazardous action (Benjamin and

Cornell, cited in Katsanos *et al.*, 2017). The above meaning of fragility can be represented analytically in Equation 2.8 (Nielson and DesRoches, 2007).

$$P[D \geq C|IM] = \Phi\left[\frac{ln(S_D/S_C)}{\beta^2{}_{D|IM} + \beta^2{}_C}\right] \tag{2.8}$$

where $\Phi(\cdot)$ is the standard normal distribution function; S_D is the demand's median estimate; S_C is the capability's median estimate; $\beta_{D|IM}$ is the demand dispersion or demand's logarithmic standard deviation conditioned on the IM; β_C is the capability's dispersion.

Fu et al. (2016) proposed the fragility analysis and principle of critical collapse curve for transmission tower subjected to wind and rain loads in order to obtain the collapse equivalent basic wind speed and most undesirable combinations of wind and rain loads corresponding to collapse status. In addition, an error analysis is carried out to ensure its effectiveness. The collapse probability for the specified equivalent basic wind speed at altitude 10 m (EBWS V^*_{10}) can be calculated as shown in Equation 2.9.

$$P = F(x|u,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{\frac{-(x-u)^2}{2\sigma^2}}dt \tag{2.9}$$

where x is the log of the EBWS taking $ln(V^*_{10})$; u is the median; σ is the standard deviation.

2.4.3 Collapse Margin Ratio (CMR)

Huang et al. (2021) studied the impacts of sea ice collapse-resistance performance of the 60 m tall wind turbine tower based on a simplified calculation model. The experiment is carried out on a shaking table simulation test device (ES-15). Tianjin, China in 1976 and Kobe, Japan in 1995 seismic waves were used for the experiment. The impact of sea ice on tower failure was assessed using the IDA approach. The link between the earthquake fortification demands and actual seismic anti-collapse according to the CMR recommended in ATC-63 is evaluated to measure the effect of sea ice on the seismic anti-collapse performance of the tower. CMR is defined as shown in Equation 2.10.

$$CMR = \frac{PGA_{50\%}}{PGA_{design}} \tag{2.10}$$

where $PGA_{50\%}$ is the earthquake intensity that would cause structural collapse if 50% of all seismic wave inputs; PGA_{design} is the highest earthquake intensity applied in a structural design.

Li et al. (2014) assesses the impact of soil-structure interaction (SSI) on the seismic collapse resistance of Shanghai Tower, a 632 m tall super-tall building. The ANSYS software predicts the collapse mode and phase while taking into consideration the SSI, as well as the effect of the SSI on the capability to resist failure and collapse sequences, using refined FE and simplified analytical models of the foundation and nearby soil. El-Centro in 1940 was used as the ground motion input in this analysis. The IDA analysis is used to determine the crucial ground motion intensity that leads to structural failure. CMR is used to determine the capability to withstand structural failure in the investigation of structural seismic collapse prevention. CMR is determined using PGA as the fundamental ground motion intensity evaluated in this analysis as shown in Equation 2.11.

$$CMR = \frac{PGA_{Collapse}}{PGA_{MCE}} \tag{2.11}$$

where $PGA_{Collapse}$ is the critical ground motion intensity that leads to structural collapse; PGA_{MCE} is the ground motion intensity corresponding to the MCE level for the design. The PGA_{MCE} is 0.22g, as stated in the Chinese Seismic Design Code (GB50011-2010) due to Shanghai being an Intensity 7 zone (Ministry of Construction of the People's Republic of China, cited in Li *et al.*, 2014).

2.5 Summary

A telecommunication steel tower is evaluated under seismic excitation in this study, which includes both far-field and near-field ground motions. This is because the lack of articles that looked into the telecommunication tower under seismic excitation that may lead to a tower prone to seismic excitation, causing the tower to fail or collapse easily. Therefore, vulnerability assessment of the telecommunication steel tower under seismic excitation must be carried out.

The Nonlinear Time History Analysis (NL-THA) is performed under different types of seismic excitations in order to obtain the Incremental Dynamic Analysis (IDA) curve accompanied by three performance limit states. This is a summary of the seismic performance of a tower that has been subjected to seismic excitation, from elastic to plastic behavior until collapse. The threat of seismic effect on the tower models, which are used to determine the chance of damage to frame systems, will be estimated using a fragility analysis based on the three performance limit states. Furthermore, Collapse Margin Ratio (CMR) is a valuable tool for determining the impact of seismic on the seismic performance of the tower. Last but not least, the plastic hinges are assigned to the frame members of the tower.

In this study, engineers were able to design a telecommunication steel tower that can withstand excitation from far-field and near-field ground motions in addition to wind effects. In addition, multiple design codes, specifications and design provisions may suggest simpler dynamic methods for the seismic estimation of the tower.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this Chapter 3, the overall flow of the study starting from the desk study towards the seismic analysis will be shown in Figure 3.1. The design of the telecommunication steel tower including defining the size and dimension of the frame section, materials properties as well as steel grade according to the standard specification will also be further discussed in this chapter. In ETABS software, the FE model of telecommunication steel tower will undergo nonlinear dynamic analysis, which is the Nonlinear Time History Analysis (NL-THA) by using different types of ground motions with different intensities. The overall procedure in ETABS software is shown at the Appendix A. The vulnerability assessment of the telecommunication steel tower will be carried out. The Incremental Dynamic Analysis (IDA) method was used to assess the tower's seismic vulnerability. Furthermore, the fragility curves are then generated using a normal distribution method based on three structural performance levels that are proposed in FEMA 356, which are Immediate Occupancy (IO, SDR = 0.5%), Life Safety (LS, SDR = 1.5%) and Collapse Prevention (CP, SDR = 2.0%). In addition, a Collapse Margin Ratio (CMR) is determined using the fragility search method collected from the IDA that is described by FEMA P695. Last but not least, plastic hinges are assigned to the frame members of the telecommunication steel tower.