THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

國家鋼結構工程技術研究中心香港分中心
Chinese National Engineering Research Centre
For Steel Construction (Hong Kong Branch)

Address: Hong Kong Polytechnic University, Phase 8, Hung Hom, Kowloon, Hong Kong.
Telephone: (852) 3400 8451 Email: cnerc.steel@polyu.edu.hk Website: https://www.polyu.edu.hk/cnerc-steel/

Project Title: Seismic performance and resilience of steel buildings using high strength steel

Principal Investigator: **Dr. You DONG (CEE)**

Project Team Members: **Dr. Peng YUAN** **Mr. Ghazanfar Ali ANWAR**
Miss Yahan LI **Mr. Hongyuan GUO**

Project Outline:

Recent earthquakes have highlighted additional losses linked to the resilience of damaged infrastructure. Environmental impact, as performance indicator, has also received increased attention within performance-based earthquake engineering. In this research project, a combined probabilistic framework is proposed to assess seismic risk, sustainability and resilience of building structures. The framework utilizes three-dimensional inelastic fiber-based numerical modeling approach to develop limit states associated with performance levels considering seismic risk, sustainability, and resilience. Additionally, the proposed approach considers uncertainties in the building performance and consequence functions of structural and non-structural components. Nowadays, there have been significant developments in steel processing and improvements in industrial processes allowed the achievement of High Strength Steel (HSS) with very attractive properties. However, use of HSS is limited by current Chinese Code for Design of Steel Structures GB 50017 and Code for Seismic Design of Buildings GB 5001. It is important to determine whether HSS could be used in seismic structures and how to use HSS in seismic resistant structure by considering loss, resilience, and sustainability. In this research project, the key issues associated with the application of HSS in seismic structures by considering structural performance, loss, resilience, and sustainability are pointed out and discussed. The proposed approach can aid the development of next generation of performance-based engineering incorporating both resilience and sustainability.

Scope of Work:

The major scopes of this project are listed as follows:

Task (1). *Seismic performance assessment of buildings based on FE modelling*
This task aims at providing the description of the methodology adopted in order to assess the nonlinear behaviour of the illustrative building. The focus is on the criteria to be assumed to

investigate the performance objectives by using numerical model. The nonlinear analyses both static and dynamic are performed by considering the nonlinear behaviour. The numerical models are developed using the nonlinear finite element-based software.

Task (2). *Performance-based earthquake engineering*

Though the structures subjected to recent seismic events obtained a good behaviour concerning the life safety designed by the current codes, severe damages on structures, as well as economic loss due to lack of use and repair cost are unexpectedly high. Hence, the codes are in a process of fundamental change, and the goal is to reduce these high losses. In order to solve this issue, performance-based design (PBD), expressed in terms of performance criteria when the structure is subjected to different seismic hazard levels represented by either magnitudes or accelerations, will be developed to aid the design and damage assessment.

Task (3). *Resilience and cost-benefit analysis*

Within this phase quantitative assessment methodologies will be established to assess the resilience and economic metrics. The PBE proposed in the previous phase has the potential to assess the quantitative sustainability metrics considering performance levels. The consequences associated with the different performance levels include both direct and indirect consequences, and will be assessed.

Task (4). *Application of the developed probabilistic sustainability and resilience approach to buildings using HSS*

Project Progress:

Up till now, a probabilistic seismic sustainability- and resilience-informed assessment methodology has been developed and applied to buildings utilizing performance-based assessment procedures. The seismic sustainability and resilience assessment framework proposed in this research project is outlined in Figure 1. Step 1 starts with building a detailed finite element model. A suit of earthquake ground motions is selected, and IDA is performed to develop fragilities at immediate occupancy (IO), life safety (LS), collapse prevention (CP), and collapse (C) limit states. In Step 2, three hazard scenarios are considered with 50%, 10%, and 2% probability of exceedance in 50 years of a structure. Non-linear time history analyses are performed to evaluate structural response in terms of story drifts, floor accelerations, and velocities, among others. Drift sensitive structural components, drift sensitive non-structural components, and acceleration sensitive non-structural components are identified, and component-level damage assessment is performed using fragility functions. In the Step 3, repair actions are determined for the considered structural and non-structural components following the repair descriptions provided in fragility specifications of FEMA methodology. The material quantity take-offs are carried out of whole building for collapse condition and repair actions are utilized for non-collapse scenario. Seismic sustainability is thus evaluated by quantifying equivalent carbon emissions using the probability of damage and collapse scenarios. In Step 4, probabilistic seismic resilience can be quantified utilizing residual functionality of a building and its recovery to pre-event functionality state at the end of recovery time. The time-variant functionality over investigated period can thus be determined, and resilience can be computed by integrating the time variant functionality. Performance based assessment methodology used for seismic sustainability and resilience quantification is discussed further.

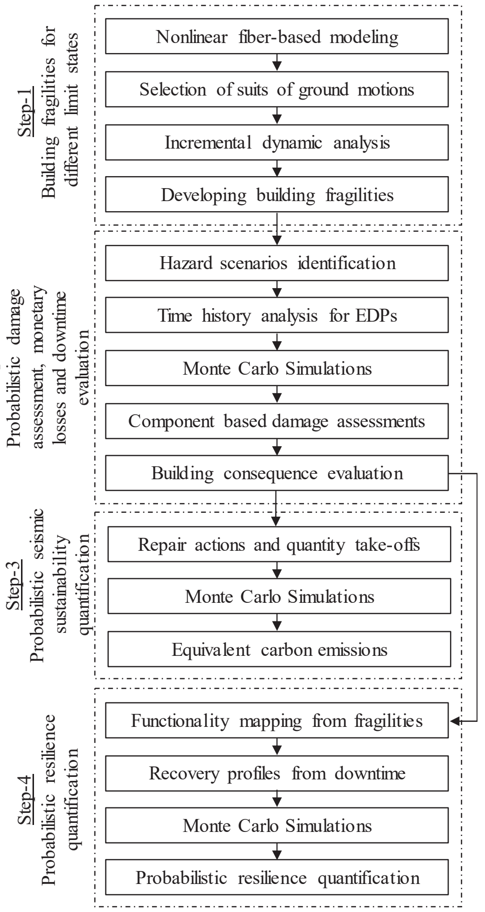

Figure 1. Probabilistic sustainability and resilience quantification framework

Task (1-2) Performance assessment based on nonlinear time history analysis and IDA

To start with, the nonlinear time history analysis is applied to the selected building, which is assumed to located in the earthquake-prone region as indicated in Figure 2. Future study would focus on the steel buildings using HSS. The building has the same story height of 4.57 m and bay span of 9.144 m as displayed. The steel structural components for the 3-story building are described in existing paper. The steel used in the buildings has a nominal strength of f_y = 345 MPa. In the conventional building, moment resisting and gravity columns are fixed and pinned at the base; fixed connections are assumed at all beam-column joints at the base level in the isolated building. The steel stress-strain and moment-curvature relationships are assumed to be bilinear with a strain hardening ratio of 3%. The columns are modeled by using force-based nonlinear beam-column elements and gravity beams are modeled using elastic beams with moment releases at both ends in OpenSees. Fiber-based modeling technique is used for the performance evaluation of pre-standard structure under earthquake hazard. Incremental dynamic analysis was performed using nonlinear analysis software ZUES-NL. Nonlinear material properties are used to represent steel behavior. Structural members are modeled using Cubic Elasto-Plastic Frame (CEPF) elements, which are capable of modeling steel yielding. CEPF elements are also capable of effectively modeling nonlinear geometric and material properties in space frames. IDA analysis was performed using carefully selected twenty far field earthquake records based on epicentral distance, magnitude, soil conditions, PGA and a/v ratios. ASCE gives limit states with respect to Inter-story Drift Ratios (IDR) for each performance criteria. An IDR of 0.5%, 1%, and 2% is considered for IO, LS, and CP performance limit states, while dynamic instability is considered for the collapse limit state. Building fragility curves developed using IDA are plotted in Figure 2. Given the fragility curve, the structural repair losses are also calculated. The repair losses calculated using damage ratios, building replacement cost and PoEs of building fragility curves are 1.19×10^5, 9.35×10^5, and 1.44×10^6 for three scenarios, respectively.

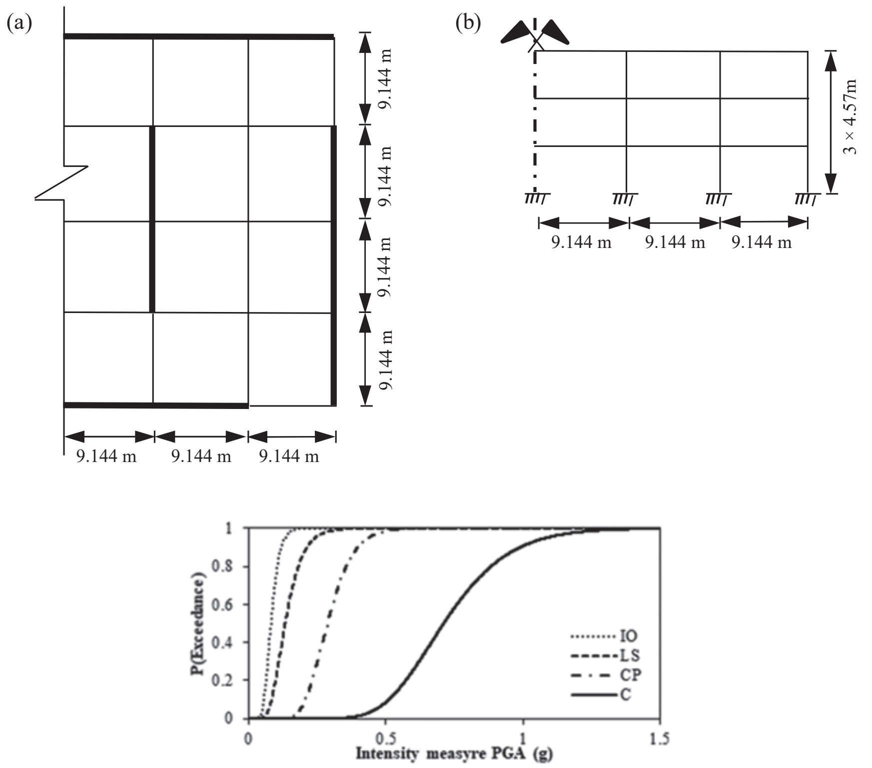

Figure 2. Investigated building and fragility curves

Task (*3*) *Resilience quantification*

Resilience is represented by its functionality and can be associated with four attributes: *robustness*: the ability to withstand an extreme event without complete failure; *rapidity*: the ability to recover from an extreme event efficiently and effectively; *redundancy*: reserve or substitutive structural components or systems; and *resourcefulness*: efficiency in identifying problems, prioritizing solutions, and mobilizing. A resilient structure not only withstands from an extreme event but also recovers efficiently and in timely fashion which is a function of technical and organizational skills of the community as well as social and economic conditions. Mathematically, resilience can be evaluated by integrating the functionality curve over time as indicated in Figure 3.

$$\mathrm{RS} = \frac{1}{\mathrm{T_r}} \int_{\mathrm{t_0}}^{\mathrm{t_0+T_r}} \mathrm{Q(t)dt} \tag{1}$$

where Q(t) is the functionality; t_0 is the time of occurrence of the extreme event and T_r is the time of investigation of functionality. As shown, the three functionality states associated with the functionality can be defined as follows:

(1) Reliability state (S_I): Pre-event functionality state where building is considered to have baseline functionality (i.e., the building is functional or in an original state before the occurrence of a hazard event);
(2) Recovery state (S_{II}): Post-event functionality state where the building is considered to have loss of functionality depending upon the robustness of the building, and time variant functionality regain as a result of repair efforts. Two types of repair schemes are defined for functionality recovery (i.e., series repair scheme where building is repaired one story at a time termed as slow-track and parallel repair scheme where all the stories are repaired simultaneously termed as fast-track). The repair efforts are an attribute of resourcefulness and redundancy of the system; and
(3) Recovered state (S_{III}): building functionality after the recovery efforts (i.e., building regains loss of functionality)
(4)

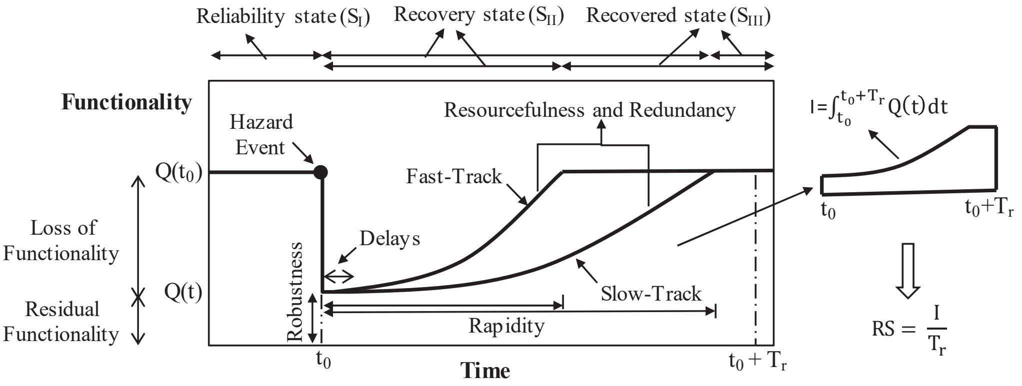

Figure 3. Resilience assessment under hazards

Performance limit states (i.e., IO, LS, CP, and collapse) are considered for the determination of residual functionality. Residual functionality also considered as the robustness of a building system can be quantified from the building performance limit states. The uncertainties associated with functionality are incorporated using triangular distribution with lower bound, upper bound and mode corresponding to IO, LS, and CP as (0.7, 0.9, 0.8), (0.4, 0.6, 0.5), and (0, 0.2, 0), respectively. The residual functionality corresponding to no damage is 1 and for collapse of a building is 0. Monte Carlo simulations are performed for the uncertainty modeling of residual functionality against different limit states and corresponding expected values for three levels are determined (i.e., 0.52, 0.22, and 0.15 for FLE, DLE, and MCE). Residual functionalities are used to calculate resilience under investigated time interval using Eq. (1).

Repair times are represented as worker days required to complete repairs, while building downtime is the total time required for a building to complete all repairs. Downtime is calculated using two schemes (i.e., parallel (fast-track) and series (slow-track)). In practice, neither parallel or series configuration is utilized but it covers a wide range of downtime, and actual downtime is presumed to be within this range. The repair times of damageable components are collected from FEMA report. Slow track and fast track repair schemes can provide reasonable estimate of lower and upper bounds of a building downtime and can be calculated by dividing the total repair time with the total number of workers available per floor for repairs and adding delay times. The calculated resilience at investigated time interval of 100, 200, and 300 days is shown in Figure 4 for fast-track and slow-track. The expected resilience of 0.975, 0.85, and 0.75 is observed for fast-track at investigated time period of 1000 days, while for slow-tack the expected resilience observed is 0.86, 0.42, and 0.31, respectively.

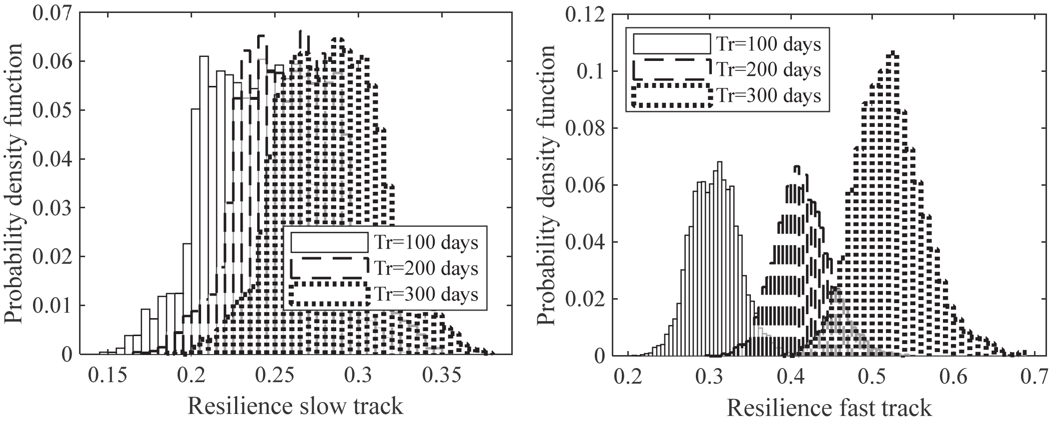

Figure 4. Distributions of resilience at investigated 100, 200 and 300 days under DLE

Project Deliverables:

In summary, this project is expected to develop a comprehensive framework of development of resilient and seismic resistant steel buildings under a scientific basis and an engineering paradigm. The resilience and cost-effectiveness of the building using HSS will be assessed and some relevant publications have been produced: one journal paper and/or two conference papers.

Project Significance

Ultimately, the proposed research proposal can facilitate design and construction engineers to work with international engineering and management practice and to enhance international visibility of "Design by Hong Kong and Construct by China".

Future Work

Within the remaining months, the proposed approach will be applied to the steel building by using HSS and conduct the cost-benefit analysis to determine the significance by using HSS in a life-cycle context considering both resilience and sustainability indicators.