13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Deterministic, probabilistic and risk-based design for progressive collapse of RC structures based on a novel method

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ABSTRACT: Progressive or disproportionate collapse is a structural failure mechanism accompanied with a significant disproportion between the initiating event and the ensuing failure consequence. Facing a possible huge economic loss and even large casualties, structures must be designed with sufficient robustness. Several structural design codes and standards have presented guidelines to increase the robustness of structures. However, these guidelines are largely of deterministic nature and may not be effective, because structures involve large variation in loading, material properties, etc. These variations can lead to significant uncertainty in the degree of robustness of structures and should be dealt with in a probabilistic framework. Based on a new direct design method developed by the authors recently, this study showed that how probabilistic and risk-based design for progressive collapse can be accomplished from a case study. The method can not only help engineers quickly conduct probabilistic performance-based design of structures against progressive collapse, but also communicate with stakeholders more efficiently if adopting risk-based design strategy.

1. INTRODUCTION

Robustness defines the ability of a structure in arresting progressive collapse under abnormal loadings. Facing the possibility that a structure collapses may lead to huge economic loss, large deaths and injuries, and possible social and environmental consequence, structures must be designed with sufficient robustness.

Currently several structural design codes and standards (DoD, 2013; GSA, 2013) have provided guidelines to ensure robustness of structures. Acceptable criteria are based on safety factors or deformation limits. In general, important structures such as administrative offices, monumental or iconic buildings, and large-span bridges should have larger robustness than regular residential, commercial, and institutional buildings. To satisfy this differentiating robustness requirements, a performance-based design approach is palatable. (Marchand and Stevens, 2015).

However, the guidelines for progressive collapse design in the current codes and standards are still rudimentary, and they are largely of deterministic nature. It is questionable whether structures designed by the deterministic method would be reasonable and effective, given that the inherent uncertainties. Probabilistic design is therefore an alternative method. To encourage stakeholders to more actively participate in the design stage of buildings, risk-based design methods seems to be even more suitable than the previous two methods (Izzuddin et al., 2012). However, the probabilistic and risk-based design strategies require great computational efforts that may not be affordable in everyday design setting.

The current study proposes a fast and simple design method for progressive collapse when adopting these three design philosophies. In the following, Section 2 briefly presents the computational approaches for deterministic, probabilistic, and risk-based optimal design formulations. Section 3 shows how these computational approaches are adopted to satisfy the design requirement by a RC frame structure. Section 4 discusses the advantages the proposed methods, followed by a conclusion.

2. DESIGN PHILOSOPHIES

2.1. *Damage states*

Under one key element removal scenario, three damage states of RC frame structures are defined as:

- I: Minor damage due to yielding of reinforcement. For simplicity, chord rotation angle of a beam reaches 0.5% can be seen as minor damage.
- II: Extensive damage due to large deformation. For simplicity, chord rotation angle of a beam reaches 15% can be seen as extensive damage.
- III: Total collapse due to rupture of rebar.

It should be noted that although this series of damage states are adopted in the present study, other possible series of damage states can also be adopted (ElSayed et al., 2015; Brunesi and Parisi, 2017; Yu et al., 2017).

2.2. *Deterministic design*

In the current study we adopted the newly proposed virtual thermal pushdown approach (He et al.) for progressive collapse deterministic-based design of a RC structure. It can be decomposed into three steps:

1. Represent the amount of reinforcement in beams (and slabs for three dimensional problems) of a RC structure by the thermal properties of the rebar material. After a structure is designed for gravitational and lateral actions with reinforcement amount $\mathbf{A}_0$, increase the amount to a very high value $\mathbf{A}_n$. Build a steel material type in finite element software with temperature-dependent property where the whole stress-strain curve of reinforcement is scaled from one to $\mathbf{A}_n/\mathbf{A}_0$ that reflects the reinforcement amount's change from $\mathbf{A}_n$ to $\mathbf{A}_0$. Then construct a finite element model for the enhanced designed structure with the built reinforcement material.
2. Conduct virtual thermal-mechanic analysis to derive the virtual thermal pushdown curve. The virtual nonlinear thermal pushdown analysis of the extremely reinforced design $\mathbf{A}_n$ starts with a conventional nonlinear pushdown analysis under gravitational load (i.e., dead load and live load) with the prescribed column removal scenario. The structure would stay at elastic state or state with very small deformation because of the large amount of reinforcement. After that, the virtual temperature is increased incrementally. During the whole process, the global structural engineering demand parameter (EDP) such as vertical displacement and chord rotation angle, etc., are recorded and plotted against temperature.
3. Determine the amount of reinforcement at any given performance target from the derived virtual thermal pushdown curve, such as the allowable chord rotation angle.

2.3. *Probabilistic design*

Although there are several probabilistic analysis that incorporated the occurrence probability of abnormal events and the subsequent failure probability of the compromising component (Parisi, 2015) , it is more practical to deal with the conditional failure probabilities given a major element removal scenario.

Monte carlo simulation method can be adopted to obtain the probabilistic properties of the structure. A series of virtual thermal pushdown curves are obtained for each random sample. Then the typical percentiles of passage of target limits can be extracted from these curves. Given any limit state and any specified target failure probability, the design enhancement degree can be rightly determined (see Figure 3). Advanced probabilistic methods can be obtained to improve the quality of samples by Latin hyper cube sampling method or the probability density evolution method.

2.4. *Risk-based design*

The risk of progressive collapse of a building under one key element removal scenario can be assessed as

$$R = C_B + p_{f,\mathrm{I}} C_{f,\mathrm{I}} + p_{f,\mathrm{II}} C_{f,\mathrm{II}} + p_{f,\mathrm{III}} C_{f,\mathrm{III}} \quad (1)$$

where C_B is the construction cost for the building; $C_{f,\mathrm{I}}$, $C_{f,\mathrm{II}}$ and $C_{f,\mathrm{III}}$ represent the losses of the I, II, and III damage states; $p_{f,\mathrm{I}}$, $p_{f,\mathrm{II}}$ and $p_{f,\mathrm{III}}$ represent the probabilities of the I, II, and III damage states. The fragility curves, as well as failure probabilities, against with the enhancement strategy can be obtained from the multiple virtual thermal pushdown curves (see Figure 4). The costs are specifically determined for different structures. Then the optimal design can be obtained by minimizing the total risk defined in Equ 1 (see Figure 5).

3. CASE STUDY: RC FRAME STRUCTURE

3.1. *Structure description and design for dead load and live load*

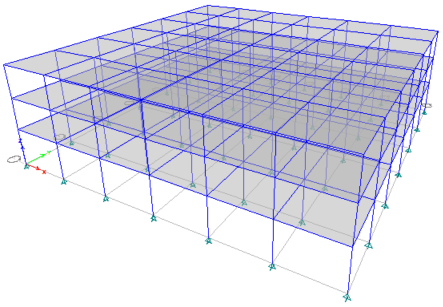

Figure 1: 3D view of the analyzed building.

A three-storey, six-bay-by-six-frame RC structure is selected as the case study from He et al. (2019). The three dimensional view is shown in Figure 1. The span length is 6.0 m in both directions. The height of the bottom storey is 4.2 m and that of the upper two storeys is 3.6 m. The depth of slabs are 150 mm, with reinforcement ratio be set as 0.4% in both two directions and both top and bottom levels. The concrete cover of slabs is 15 mm at both the top and bottom sides. As for loads, the imposed dead load is 2.5 kN/m^2 and 3.5 kN/m^2 for floors and roof, respectively, while the nominal live load is 3.5 kN/m^2 and 2 kN/m^2 for floors and roof, respectively. In addition, all beams are subjected to a distributed dead load of 5 kN/m to account for lightweight infill walls. The structure is designed for gravitational load only, while lateral actions such as wind and earthquake are ignored. The structure is designed as per Chinese code for design of reinforced concrete structures (GB50010, 2010), which is similar to the Euro code (CEN, 1992). Detailed information can refer to He et al. (2019).

3.2. *Finite element model*

Although 3D model should be taken for progressive collapse analysis, here we only take one planer middle frame to show the three design strategies, for the sake of simplicity. The planar frame is subjected to half of the loads on the immediately adjacent two side slabs, as well as it's self weight.

Instead of using high-fidelity finite element model (Pham et al., 2017; Yu et al., 2018), we adopt macro models (Bao et al., 2008) because of its efficiency. In particular, fiber models of beams and columns (Bao et al., 2008; Fascetti et al., 2015) are adopted. Opensees (Mazzoni et al., 2006) is adopted to model the structure. In the model, each beam-span is discretized into twenty displacement-based beam-column elements, each assigned two integration points. Columns are meshed as one force-based element. As for the constitutive models, the uniaxial *concrete02* material model is used for both unconfined and confined concrete fibers, and *steel02* material model for steel rebar fibers. Slabs are considered by using T-shape beams. The pushdown analysis is carried out under a displacement control scheme, while the gravitational load is proportional to the sum of dead load and a half of live load (DL + 0.5 LL).

3.3. Deterministic design

According to the developed model, Figure 2(b) (the black solid line) shows that the structure would collapse under the middle column removal scenario, as both the collapse resistances in compressive arch action stage and tensile catenary action stage are less than the load factor 1.0.

Table 1: Enhancement Strategies.

Enhance degree	**Beams**
0	No enhancement.
1	Make the amount of top rebar in beams the same as its maximum value along the element.
2	Make the amount of bottom rebar in beams the same as its maximum value along the element.
3	Make the amount of rebar at top and bottom the same as its larger value along the element.
4	Make the amount of rebar at top and bottom to be the maximum allowable value.

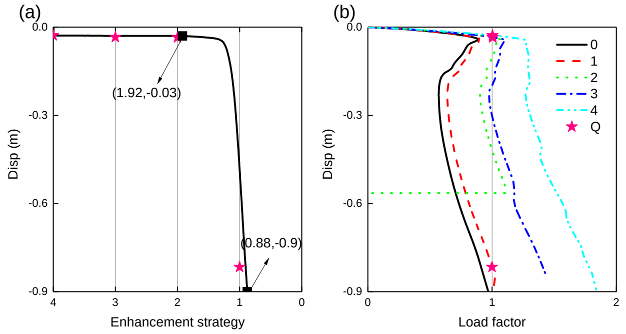

Figure 2: Deterministic design against progressive collapse: (a) virtual thermal pushdown analysis; (b) five pushdown analysis.

Therefore, in order to arrest the progressive collapse of the structure, the structure should be enhanced. Current methods to secure RC frame structure in the context of progressive collapse lies in the enhancement of either compressive arch (or membrane) action or tensile catenary (or membrane) action. Methods could be enlargement of section size , increase of reinforcement amount (in reasonable location) (Alogla et al., 2016; Yu and Tan, 2013), lengthening the anchorage length or change of splice methods to ensure tensile action, and increase of the constraint effect, etc. Among these methods, increase of reinforcement amount is the simplest approach, since the dimensions of beam and column elements are usually determined at the initial stage of the design mainly to satisfy building code requirements for normal actions (Hajirasouliha et al., 2012). Five designs (including the original one) with different enhancement degrees are listed in Table 1.

Using the virtual thermal pushdown analysis, the virtual thermal pushdown curve is obtained, as shown in Figure 2(a). When the performance is minor damage, the enhancement strategy index can be calculated as 1.92. When the performance is extensive damage, the enhancement strategy index is 0.88. The ultimate design reinforcement amount can be determined accordingly. It is noted that the displacements under load factor 1.0 of the normal pushdown curves are matched well with the virtual thermal push curve.

3.4. Probabilistic design

The parameters that mainly affect the response of the structures to column removal scenarios are assumed to be random variables (RVs). Other parameters were considered as deterministic variables. For RC frame structures, considered uncertainty parameters as shown in Table 2. According to the sensitivity analysis in Yu et al. (2017), dead load, live load, yielding strength of rebar, and compressive strength of concrete are among the most important parameters.

Monte carlo simulation is adopted to obtain a series of virtual thermal pushdown curves. Results of 100 simulations are shown in Figure 3. The fragility curves corresponding to these three damage states can be extracted from the virtual thermal pushdown curves, as shown in Figure 4.

Table 2: Random properties of parameters.

Paras	Bias	COV	Dist	References
DL	1.06	0.07	Norm	GBJ68 (1984)
LL	0.25	0.57	Gumb	GBJ68 (1984)
f_c	1.43	0.19	Norm	GBJ68 (1984)
f_y	1.13	0.072	Norm	Wang et al. (2013)

When the performance is minor damage with 16% probability, the enhance strategy index can be calculated as 1.36. When the performance is extensive damage with 16% probability, the enhance index is smaller than 0, which means there is no need to enhance the structure.

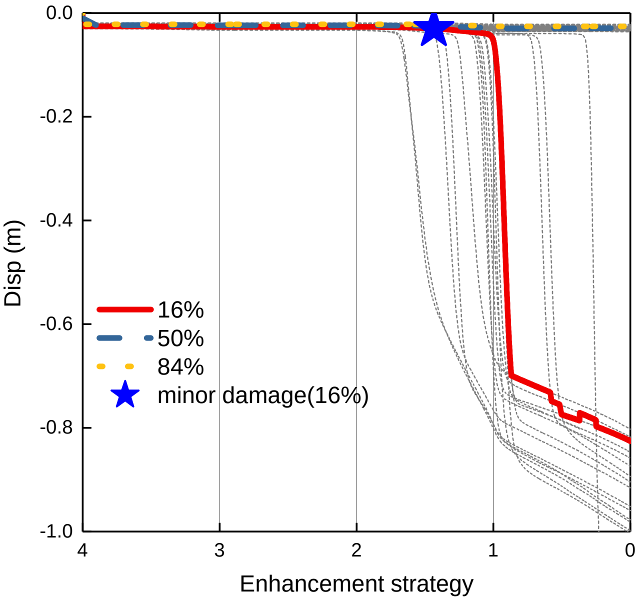

Figure 3: One hundred push down curves.

3.5. *Risk-based design*

The building cost C_B is decomposed to the structural part and other part. The structural part cost is assumed to contribute 20% of the total cost, then the risk of the building with consideration of different design is assessed as:

$$R = C_B(0.2\alpha + 0.8 + p_{f,\mathrm{I}}\eta_1 + p_{f,\mathrm{II}}\eta_2 + p_{f,\mathrm{II}}\eta_3) \tag{2}$$

where α represents the ratio of enhanced structure's cost to the original design's; $\eta_1 C_B$ represents the cost for minor damage that need to repair; $\eta_2 C_B$ represents the cost for extensive damage that need to replace; $\eta_3 C_B$ represents the cost for collapse that injuries and casualties may occur. In Equ 2 we assume the architect and facility cost do not change when the structure is strengthened.

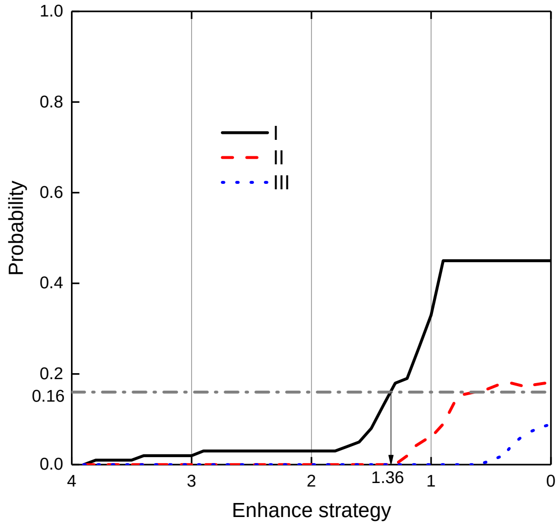

Figure 4: Fragility curves.

The value of α is determined by the material volume of concrete and reinforced rebars adopted. The cost of rebar is estimated as 4000 Chinese yuan (600 US dollar) per ton, while the cost of concrete is estimated as 600 Chinese yuan (90 US dollar) per cubic meter. The weight of reinforcement and the volume of concrete is calculated according to the planar frame, including beams, columns, and two half span slabs.

η_1 is estimated as 0.123, according to the damage state with drift ratio equal to 0.40%-0.5% including structural and non-structural contents (El-Khoury et al., 2018). η_2 is estimated as 1.0 for replacement as the structure has reached extensive damage and should be replaced, while non-structural components are also assumed to be replaced because of glazing and facade damage. η_3 was estimated between 7.6 to 19.7 for the World Trade Center towers in the 911 event (Faber, 2004). These values can be seen as the upper values as the social loss was rather huge. Here η_3 is assumed to be 5.0 (Wen and Kang, 2001).

Figure 5 shows the risk analysis result with different enhancement strategy. The bottom rectangular part presents the invariable assumption about the non-structural building cost. The cost of structural increases nearly linear from no enhancement to a large degree of enhancement with a rather smooth slope. When the degree of enhancement is small, there is significant risk of damage or collapse. The optimal design point is when the structural enhancement degree equals 1.6, or the initial total cost of the building increases 1.97%. The value is well in accordance with the values adopted in (Stewart, 2017).

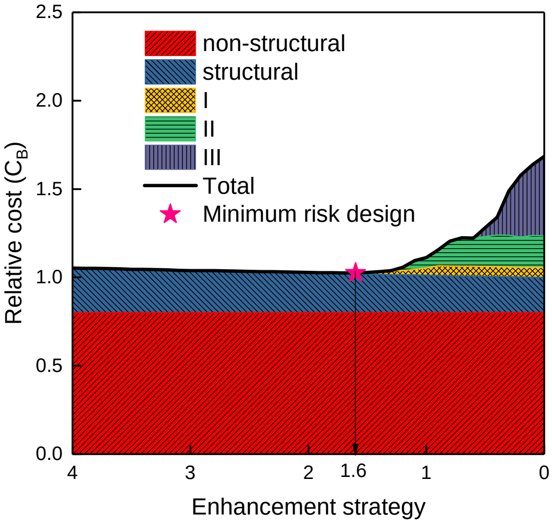

Figure 5: Risk assessment.

4. DISCUSSION

4.1. The conditional nature of element removal

We have to consider the premise that all the above design philosophies are based on one typical element removal scenario. The probability of a hazard event and the conditional probability of column removal are not considered.

Designing all building structures for progressive collapse might not be cost-effective Stewart (2017). However, for important public buildings such as key government buildings, monumental or iconic buildings, it could be reasonable to enhance them if the increased cost is relatively low. Facing the uncertainty in the future, it is preferred to strengthen these building at the construction phase rather than rehabilitate them later, since the cost is much less (Glover, 2000). In this context, we use alternative path method to design structures, without considering the possibility of the hazard occurrence rate.

4.2. Computational cost

For general probabilistic or risk based design optimization for a large structure when a large number of design parameters are involved, usually heuristic optimization methods - such as genetic and particle swarm algorithms - should be adopted(Beck and de Santana Gomes, 2012) to avoid obtaining local optimal results by mathematical programming methods. However, such heuristic algorithms are generally computational prohibitively, especially when facing large real structures.

In the context of preventing progressive collapse for RC frame structures, increase of reinforcement amount is the simplest enhancement approach, since the dimensions of beam and column elements are usually determined at the initial stage of the design mainly to satisfy building code requirements (Hajirasouliha et al., 2012). The number of design parameters is thus dramatically reduced. Furthermore, for a multi-floor RC frame structures, the enhancement strategy for the beams at each floor is set to be the same by assuming that explosion could happen at each floor and each floor should thus have relative equal robustness. In the end, only one design parameter needs to optimize if adopting the design enhancement strategies shown in Table 1. Adopting the method demonstrated, the analyzing time for probabilistic or risk-based design could be significantly reduced, making it practically acceptable for everyday design.

5. CONCLUSIONS

Facing the increasing demand for safety of building structures in the uncertain future, structural engineers should design structures against abnormal actions, such as vehicle impact, blast, gas explosion, fire, terrorist attacks. This is especially vital for specially important or ironic buildings, bridges and other facilities. Because of the importance of these structures, structural engineers should have different design approaches to meet the requirement of stakeholders. This study propose a simple but effective method for deterministic, probabilistic and risk-based design philosophies. A case study was undertaken to show how the proposed method can improve structural robustness against progressive collapse in a relative quick manner, regardless which of the three design philosophies is employed.

ACKNOWLEDGMENT

This research was partially supported by National Key Research Program of China (grant number 2016YFC0701400), National Natural Science Foundation of China (grant number 51338004), and the Discovery Grant program of the Natural Science and Engineering Research Council (NSERC) Canada. The study was conducted during the first author's visiting research at Ryerson University. The funding support from the China Scholarship Council (CSC) for the first author is also gratefully acknowledged.

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