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Robustness Assessment for Progressive Collapse of Framed Structures using Pushdown Analysis Method

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Overview of the Presentation

- Introduction
- Pushdown Analysis Method
- Quantitative Assessment of Structural Robustness
- Case Study: RC Frame
- Conclusions

Introduction

- **Background**

Ronan Point

The Great Wenchuan Earthquake, May 12, 2008

Introduction

Background

- **The progressive collapse of vast buildings in the past earthquakes demonstrated that it is very important to take into account the ability of resisting progressive collapse and robustness of generic structures under rare earthquakes**

- **There is neither a uniform theory of structural robustness assessment nor a general methodology for quantification of the progressive collapse resistance of real complex structures**

Introduction

Motivation

- A new pushdown analysis method is used to evaluate the residual capacity of damaged structures under rare earthquakes
- The residual reserve strength ratio (RRSR) is taken as a quantitative index to assess the robustness of damaged structures, and to quantify the progressive collapse resistance of real complex structures
- The effects of the duration of element removing in the process of applying the vertical load is considered

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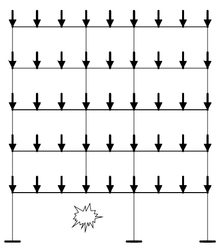
Pushdown Analysis Method

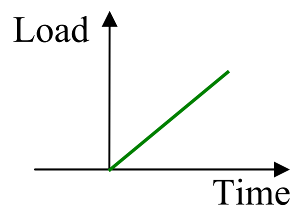
Definition of structural progressive collapse

Progressive collapse of a structure refers to the condition when the failure of a local component leads to global system failure

Uniform pushdown and bay pushdown

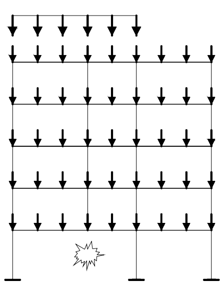


Column removed



Increase gravity load proportionally over the entire structure

Uniform pushdown



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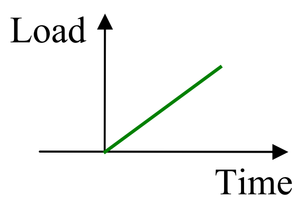
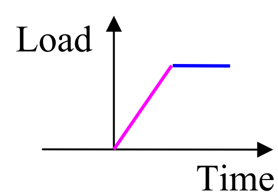


Increase gravity load proportionally in the damaged bays

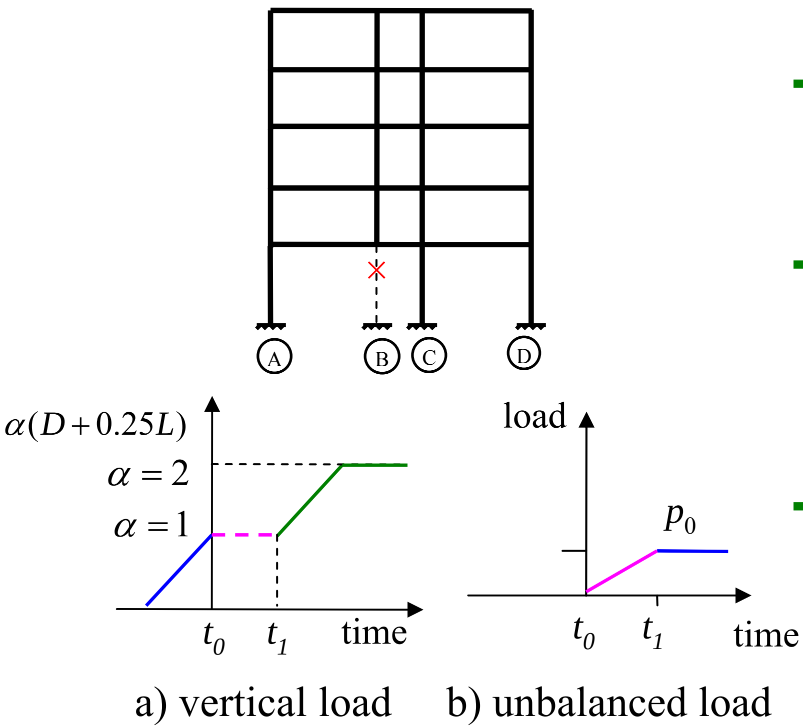


Nominal gravity load in all other bays

Bay pushdown

Pushdown Analysis Method

- **The conventional pushdown analysis procedure is revised to consider the effects of the duration of element removing**



Schematic of load applying in pushdown analysis

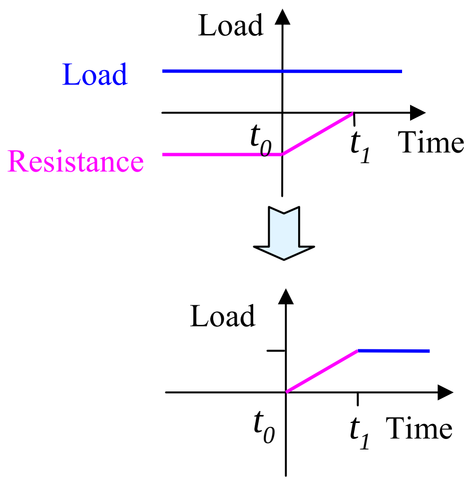
- **Firstly, apply the basic load (D+0.25L) to the structure;**
- **Secondly, remove the failed column, and apply the unbalanced load to the remaining structure in sub-steps;**
- **Finally, apply the additional load (D+0.25L) to the damaged bays until the completion of the loading or divergence of the program.**

Control criteria: the yielding state of the structure; the ultimate state; collapse.

Pushdown Analysis Method

The effects of the duration of element removing

- **The revised procedure is equivalent to releasing the failed elements step by step.**



The unbalanced load on the failed point

- **The failed column is removed within the time interval (t_0, t_1)**
- **If the duration of element removing is zero, which corresponds to a rectangular shock load**
- **If the failure of the element takes a short time, it corresponds to a shock load that has an ascending segment.**

- **In addition, the dynamic effects of the undamaged bays, the effects of the instant of element removing and the loading steps are also analyzed.**

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Quantitative Assessment of Structural Robustness

Definition of structural robustness

- The quantitative value of the robustness of a structure is obtained by a redundancy index

$$R = \frac{P_{damaged}}{P_{design}}$$

where, R is the residual reserve strength ratio (RRSR),

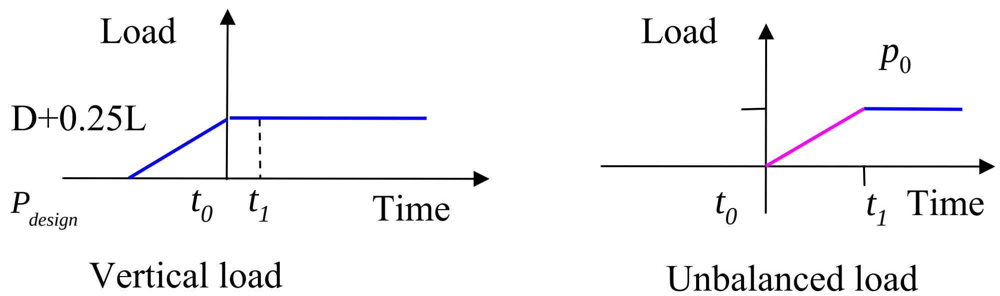
$P_{damaged}$ is the ultimate load of the damaged structure,

P_{design} is design load of the intact structure.

Quantitative Assessment of Structural Robustness

Schematic of calculation of the residual reserve strength ratio

- **Firstly, the maximum vertical displacement is obtained by dynamic analysis.**



Schematic of load applying in vertical dynamic analysis

- **Secondly, pushdown analysis is applied to the structure, P_{design} is obtained , it is the load factor corresponding to the maximum vertical displacement obtained above on the pushdown curve.**
- **Finally, determine $P_{damaged}$, which is the load factor corresponding to the ultimate load-bearing capacity of the structure on the pushdown curve.**

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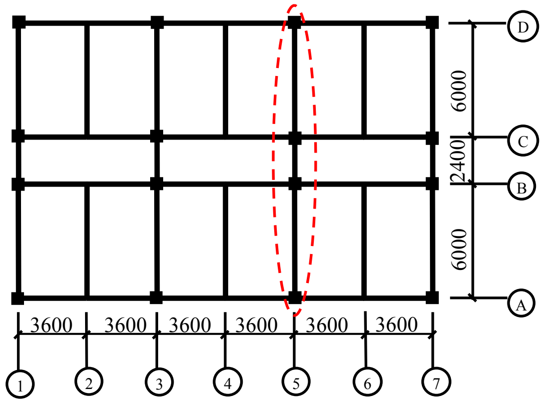
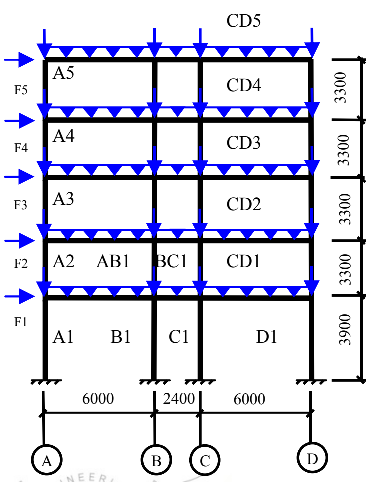
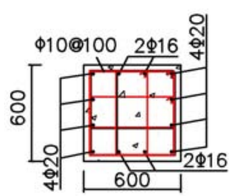
Case Study: RC Frame

Description of the structure







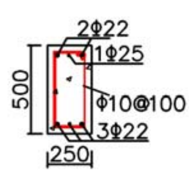


Table I. Layout of vertical load						
Location	Uniformly distributed load (kN/m)		Concentrated load (kN)			
			Edge node		Internal node	
	Dead load	Live load	Dead load	Live load	Dead load	Live load
Head floor	12.09	1.10	121.0	7.0	149.6	10.6
Middle floor	9.35	4.40	102.3	28.1	122.9	42.5
Ground floor	9.35	4.40	105.4	28.1	126.0	42.5

Table II. Structural vibration periods						
direction	Before the gravity load is applied (s)			After the gravity load is applied (s)		
	The first mode	The second mode	The third mode	The first mode	The second mode	The third mode
X	0.737	0.219	0.111	0.945	0.265	0.124
Y	0.059	0.053	0.052	0.059	0.055	0.053

Case Study: RC Frame

The material properties used in the simulations

Table III. Parameters of concrete material properties (C35)

		Peak stress	Peak strain	Ultimate stress	Ultimate strain
Unconfined		-29.76	-0.0018	0.0	-0.0046
Confined	column	-37.65	-0.0046	-12.50	-0.0271
Confined	beam	-36.20	-0.0045	-11.73	-0.0278

Note: The unit of stress is MPa.

- **Concrete is modeled by Concrete01, confinement is specified implicitly by using the confined stress-strain relationships proposed by Mander, Priestley and Park**
- **Reinforcing steel is modeled by Steel02 with 1% strain hardening**

Case Study: RC Frame

The effects of duration of element removing

- **The duration of element removing is 0.10s**

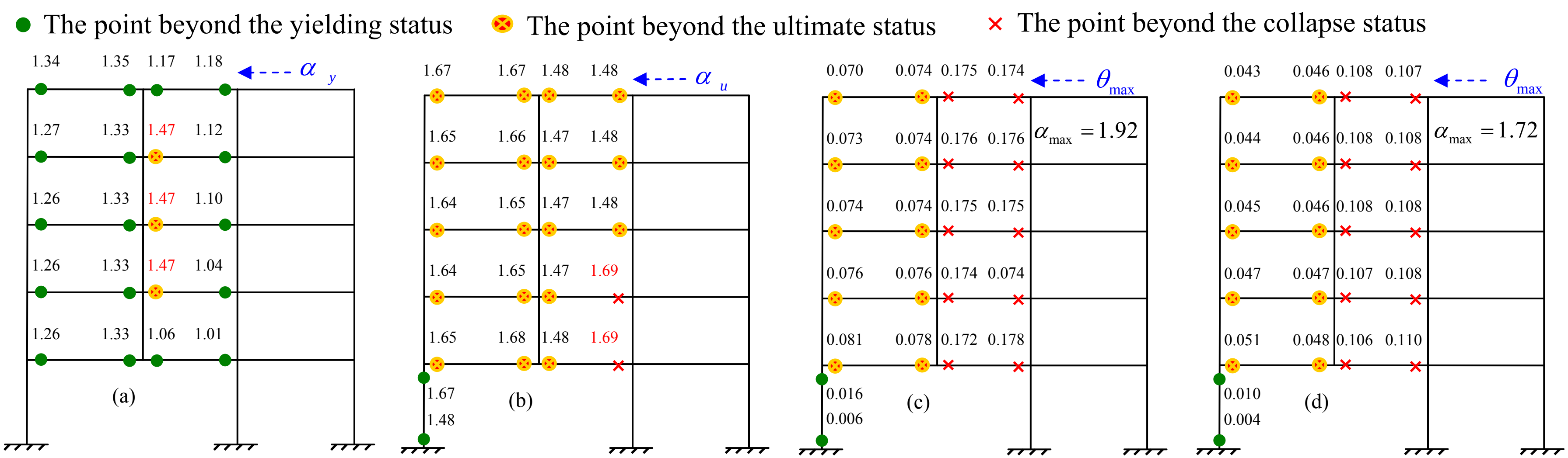
Table Ⅳ. The results of pushdown analysis considering the effects of the duration of element removing

Location of cross section	α_y	θ_y (rad)	α_u	θ_u (rad)	θ_{max} (rad)	θ_u / θ_y	$\theta_u - \theta_y$
Right side of beam BC1	1.01	0.00317	1.49	0.04171	0.17817	13.16	0.03854
Left side of beam BC2	1.04	0.00272	1.47	0.03515	0.17363	12.94	0.03243
Right side of beam BC2	1.04	0.00279	1.48	0.03798	0.17603	13.61	0.03519
Left side of beam BC1	1.06	0.00276	1.48	0.03779	0.17243	13.67	0.03503
Left side of beam BC3	1.10	0.00275	1.47	0.03528	0.17508	12.83	0.03253
Right side of beam BC3	1.10	0.00283	1.48	0.03778	0.17529	13.33	0.03495
Left side of beam BC4	1.12	0.00273	1.47	0.03524	0.17551	12.89	0.03251
Right side of beam BC4	1.12	0.00281	1.48	0.03773	0.17527	13.43	0.03492
Left side of beam BC5	1.17	0.00283	1.48	0.03800	0.17536	13.44	0.03517
Right side of beam BC5	1.18	0.00292	1.48	0.03685	0.17436	12.64	0.03393
Left side of beam AB1	1.26	0.00346	1.65	0.04167	0.08142	12.06	0.03822
Left side of beam AB2	1.26	0.00326	1.64	0.03674	0.07578	11.29	0.03349
Left side of beam AB3	1.26	0.00326	1.64	0.03576	0.07379	10.95	0.03249
Left side of beam AB4	1.27	0.00329	1.65	0.03644	0.07273	11.09	0.03316
Right side of beam AB1	1.33	0.00495	1.68	0.04324	0.07803	8.74	0.03830
Right side of beam AB2	1.33	0.00475	1.65	0.03852	0.07642	8.10	0.03376
Right side of beam AB3	1.33	0.00474	1.65	0.03750	0.07458	7.91	0.03276
Right side of beam AB4	1.33	0.00471	1.66	0.03840	0.07394	8.16	0.03369
Left side of beam AB5	1.34	0.00299	1.67	0.03682	0.07033	12.32	0.03384
Right side of beam AB5	1.35	0.00534	1.67	0.03960	0.07401	7.42	0.03427
Bottom of column A1	1.48	0.00371	-	-	0.01589	-	-
Top of column A1	1.67	0.00335	-	-	0.00648	-	-

The mean value of $\theta_u - \theta_y$ is 0.0345，the standard deviation is 0.0019，and the coefficient of variation is 0.055

Case Study: RC Frame

The effects of duration of element removing

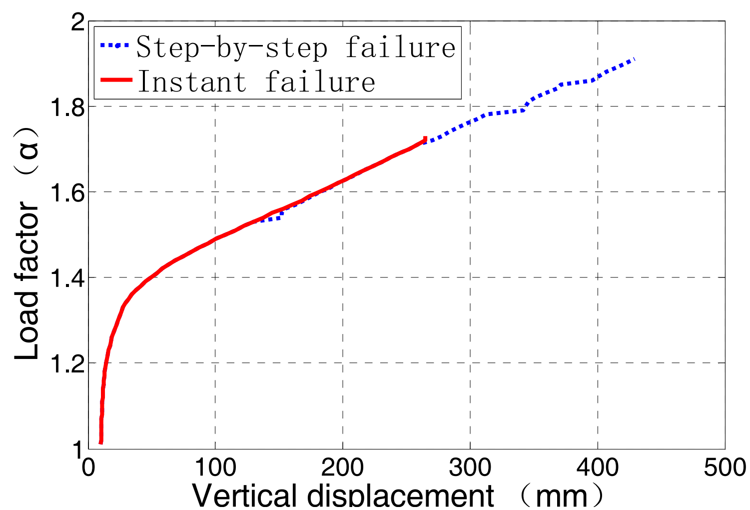


Distribution of plastic hinges of the damaged structure considering the effects of duration of element removing

- **The maximum rotation in the analysis has relations with the span of the beam, and it has nothing to do with the locations of the cross-sections; Plastic hinge occurs only in the column A1 in the whole process of the analysis.**
- **The deformation limits of the rotation degrees of components obtained in this paper is close to the limit value recommended in the UFC (0.105 rad)**

Case Study: RC Frame

- **The effects of duration of element removing**



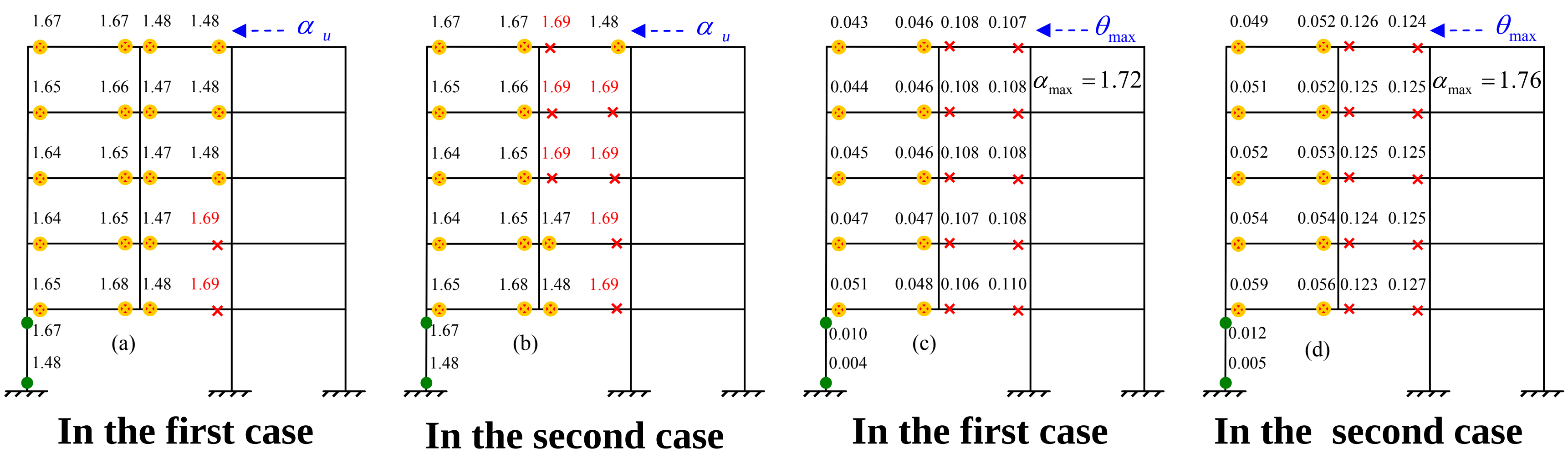
Pushdown curves of the model structures considering the effects of the duration of element removing

- **The increases of the structural robustness gained by pushdown analysis which considering the effects of the duration of element removing are of about 11.6%**
- **It has no effects on the failure modes**

Case Study: RC Frame

The effects of the instant of element removing

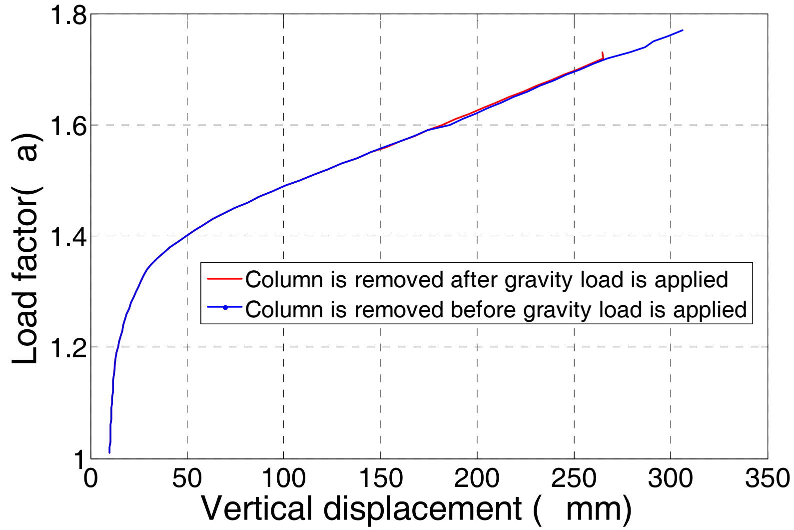
- In the first case, the element is removed after the gravity load is applied to the structure in pushdown analysis
- In the second case, the element is removed before the gravity load is applied to the structure



Distribution of plastic hinges of the damaged structure considering the effects of the instant of element removing

Case Study: RC Frame

The effects of the instant of element removing



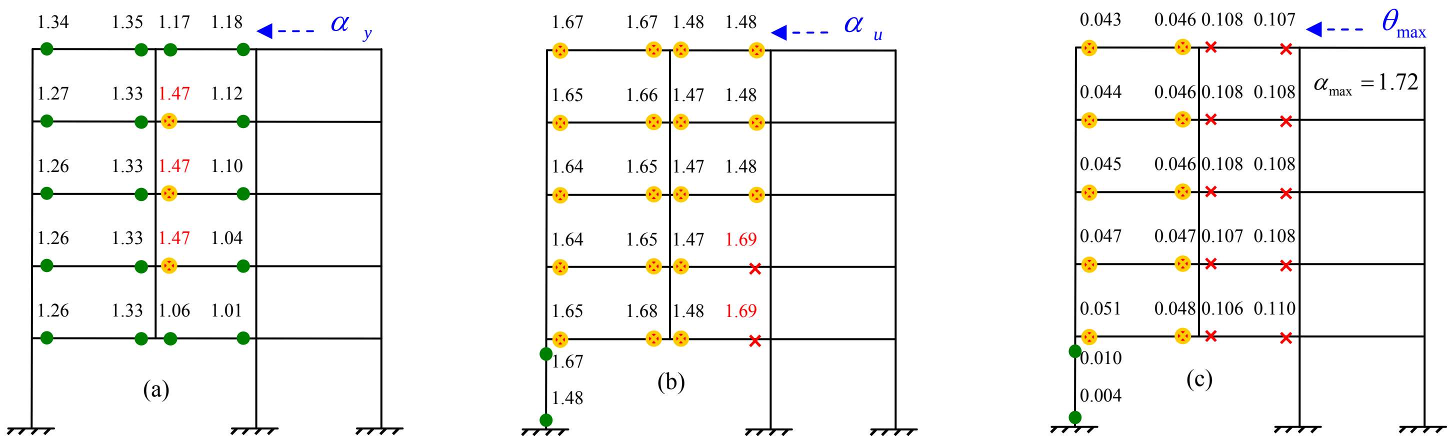
Pushdown curves of the damaged structures considering the effects of the instant of element removing

- The increases of the ultimate ability of resisting progressive collapse of the structure that obtained by pushdown analysis in the second case are of about 2.3%
- It has no effects on the failure modes

Case Study: RC Frame

The dynamic effects of undamaged bays

- **The uniform pushdown is used to investigate on the dynamic effects of the undamaged bays**

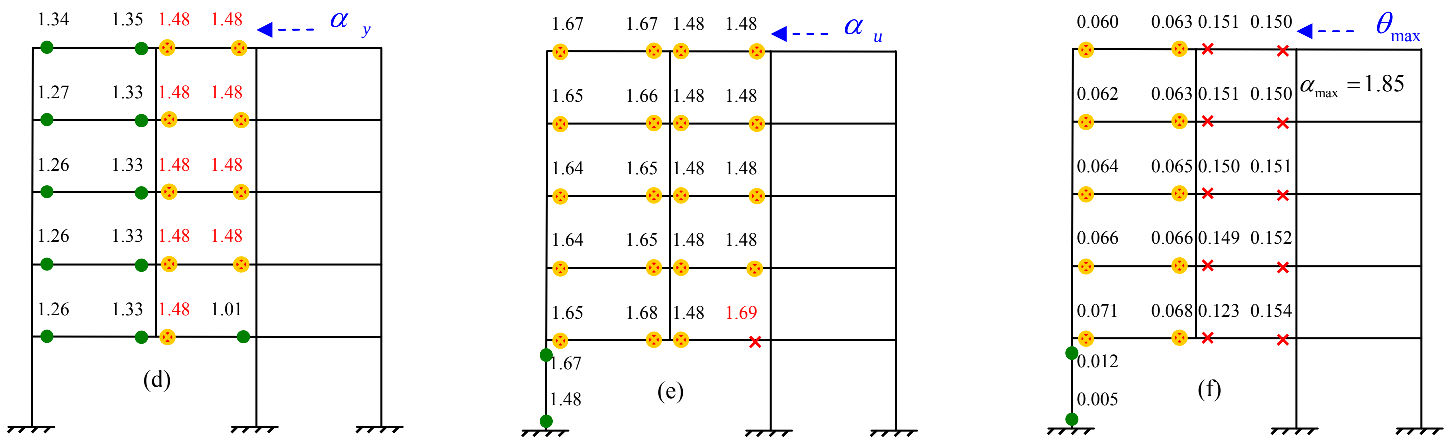


Bay pushdown analysis

Distribution of plastic hinges of the damaged structure not considering the dynamic effects of undamaged bays

Case Study: RC Frame

The dynamic effects of undamaged bays



Uniform pushdown analysis

Distribution of plastic hinges of the damaged structure considering the dynamic effects of undamaged bays

- **It has no effects on the failure modes of the structure by considering the dynamic effects of the undamaged bays**
- **The increases of the ultimate load factor obtained in the analysis which considering the dynamic effects of the undamaged bays are of about 7.6%**

Case Study: RC Frame

The effects of load steps

Table Ⅴ. The ultimate load factor obtained by pushdown analysis in different load steps

Load step	Considering the effects of the duration of element removing	Not considering the effects of the duration of element removing
0.001	1.84	1.78
0.005	1.98	1.85
0.01	1.92	1.72
0.02	0.84	2.00
0.05	0.80	0.80

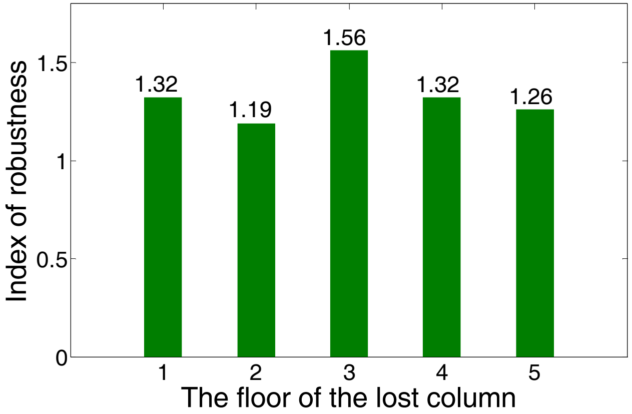
- **The failure modes of different analysis steps are the same, a smaller ultimate load factor is gained when the load step is too large or too small.**
- **The limit of rotation degree of components is suggested as the major control criteria for the failure of components or for preventing the structure from collapse.**

Case Study: RC Frame

Quantitative analysis of structural robustness

- **The pushdown analysis is performed on the damaged structure which assumes that the column in column line B on each floor is removed respectively**

Take column B1 as an example: $$R = \frac{P_{\text{damaged}}}{P_{\text{design}}} = \frac{1.72}{1.305} = 1.32$$



The robustness indices of the damaged structures assuming the columns in column line B removed for each floor respectively

- **If the smallest value is regarded as the robustness of the whole building, then it is 1.19.**

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Conclusions

- The effects of the duration of element removing Pushdown analysis considering the effects of the instant and duration of element removing, dynamic effects of undamaged bays as well as load steps is performed respectively, it is founded that they all have no effects on the failure modes of the structure, but they do have influences on the ultimate ability of resisting progressive collapse of the structure.
- The failure modes can be efficiently determined by the pushdown analysis of a structure, and the robustness of the structure can be quantitatively assessed by the residual reserve strength ratio.
- It is hoped that the method proposed by this paper will provide a practical method that the engineers could use to design more robust buildings.

The end

Thank you for your attention