Advanced Materials Research Vols. 133-134 (2010) pp 1225-1231

doi:10.4028/www.scientific.net/AMR.133-134.1225

Progressive Collapse Evaluation for Historic Building Structures

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Abstract Important historic buildings may be subjected to accidental loads during their service life. It is therefore necessary not only to evaluate their safety under traditional loads and seismic action (only in earthquake area), but also to evaluate the structural performance of resisting progressive collapse. For historic buildings, two aspects make them different from the modern buildings: the material properties are usually deteriorated to some extent, and the structural system/constructions may not meet the requirements of current design and construction codes. Considering such aspects, a method consisting of four steps to evaluate the performance of the historic buildings to resist progressive collapse is presented in this paper. Firstly, the building layout should be evaluated whether it can protect the occupants from the possible explosion. Secondly, geometrical information, structural constructions and the material properties are to be investigated in details. Thirdly, by means of tie force method and the alternate path method the performance of the structure is analyzed to resist progressive collapse. The load combinations used in the analysis are derived based on the expected service life of the structure. The failure criteria for the structural elements as well as the damage limits for the structure follow the provisions addressed in American Unified Facilities Criteria "Design of Structure to Resist Progressive Collapse" (UFC 4-023-03). Finally, based on the above information an overall evaluation is made for the probably structural retrofitting and strengthening. This method is illustrated with a case study of a steel frame historic building, namely the Bund 18 building, in Shanghai, China. Some suggestions for retrofitting and strengthening this building are also presented.

Keywords: Progressive collapse evaluation, historic buildings, tie force method, alternate path method

Introduction

Some historic buildings become landmarks because of historical or cultural reasons. These buildings may suffer accidental loads, such as terrorist bombing attacks, during their service life. Therefore, it is necessary not only to evaluate their safety under traditional loads and seismic action in earthquake area, but also to evaluate the structural performance of resisting progressive collapse under certain circumstances.

A few design approaches for progressive collapse evaluation, including tie force method, alternative path method as well as local resistance method, were adopted in current design guidelines (GSA 2003, DoD 2005). Among them, the alternative path method was widely used. With proper analysis procedure the structural damage and collapse process might be appropriately described. Additionally, other design approaches for progressive collapse evaluation, for example, from the viewpoint of seismic analysis, structural robustness, energy conservation and so on (Wang *et al*. 2009), were also under study. However, when the above methods were applied to historic buildings two aspects should be considered: on one hand, the material properties were usually deteriorated to some extent, on other hand, the design approach and the structural construction might different from the requirements of current codes.

This paper presents a comprehensive method to evaluate the performance of historic buildings to resist progressive collapse. The method consists of four steps including evaluation of building layout, investigation of structural status (geometrical information, structural constructions and material properties), computational procedure as well as evaluation results. As a case study, the performance against progressive collapse for a steel frame historic building constructed in 1923 in Shanghai was evaluated to show the application of this method.

Building Layout

Taking properly security measures will contribute to preventing the potential attacks or mitigating the effects of the attack. These measures include the various aspects such as reasonable road and traffic situation near the building, adequate standoff distance, installation of protective barriers, control of access zones, rational parking place as well as the structural strengthening measures (FEMA 2003).

Road and Traffic The distance between the building and the road nearby should be sufficient. The possibility that a large number of people gathered and stranded in the vicinity of the building should be reduced. The road nearby the building should be simple and unobstructed, which facilitates rescuing in time and evacuating safely in the event of an attack. Roads entering the building should be avoided as a straight line or measures should be taken to slow down the traffic. In this way, bomb carriers gaining access to the building by speedup are appreciably prevented.

Level of Protection and Standoff Distance Increasing the standoff distance (distance between explosion source and building) is one of the most effective way to provide protection. The standoff distance is related to explosive weight, structural type, security measures and the desired level of protection. Fig. 1 presents the relationship curves between the standoff distance, the explosive weight and explosive overpressure (Marchand and Alfawakhiri 2005). For retrofitting and strengthening of a historic building, the standoff distance may be increased for future functional requirements.

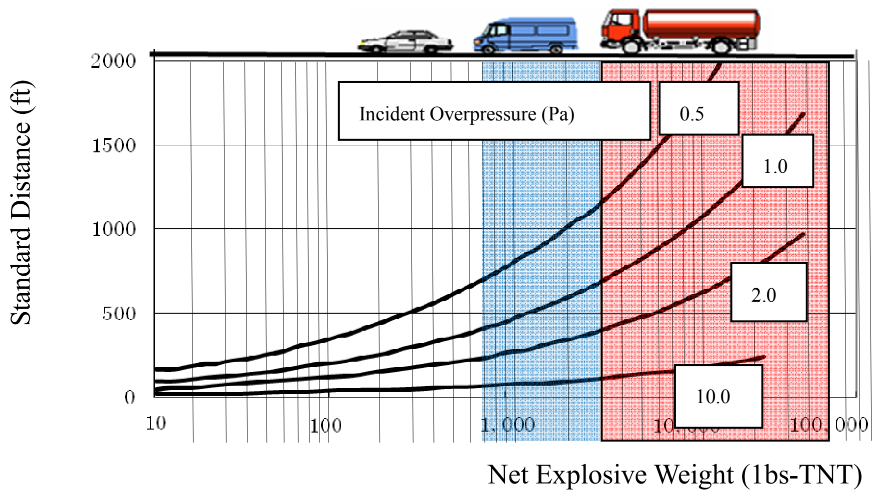

Figure 1: Vehicle bomb sizes, standoff distance and explosive overpressures

Perimeter Anti-Ram Barriers The perimeter anti-ram barriers such as planters, drains, fences, fountains, staircases or bollards may be used along the curbs, particularly on the sides of the building. These devices make it difficult to successfully execute the easiest attack scenarios such as a vehicle jumping onto the curb and ramming into the building prior to detonation. The suspicious autos can be stopped at a certain distance away from the building, which may prevent the occurrence of terrorist attack or mitigate the explosion hazard effectively. Additionally, the barriers may lead to a psychological deterrent for terrorists (FEMA 2003).

Controlled Access Zones Controlled access zones should be set at which personnel and vehicles are examined to avoid the bomb access to building interior. This is the most direct, economical and effective measure. The location of access points should be oblique to oncoming streets so that it is difficult for a vehicle to gain enough velocity to break though the access locations.

Parking Lots The parking lots and service areas should be set up outside a certain range of building to reduce the damage caused by blast. It is commended to set one–way road for ground parking lots, and to install electronic surveillance systems in underground parking. This makes the safety supervisor convenient to observe and control suspicious persons and vehicles.

Structural Strengthening In the event of an attack, damage of the structure usually cannot be avoided. Structural strengthening may help to save/rescue lives by preventing building collapse and limiting flying debris. Many technical measures may be used to improve the structural robustness. For instance, (1) bonding steel plates on the surface of beams and columns to increase capacity to resist blast, (2) improving connections between structural elements to enhance the structural integrity, (3) using catch bar system, butt glazing system or blast curtain for windows to reduce injuries to the occupants, and so on.

Investigation of Geometrical Information, Structural Constructions and Material Properties

For historic buildings, the material properties are usually deteriorated to some extent, and the design approach as well as structural constructions may not meet the requirements of current design and construction codes. As a result, the structural status should be investigated in detail.

Recent study found that the stress-strain relationship of corroded steel bars may differ from the uncorroded ones. With the increase of corrosion ratio, the ultimate strain decreases and the yield plateau may became shorter or even disappeared (Zhang et al. 2006).

Tie Force Method and Alternate Path Method

The tie force method is used to evaluate the structural integrity/construction of the building. All tie forces, including internal, peripheral, external columns or walls, corner column and vertical tie forces, should meet the requirements in design guidelines (DoD 2005).

The alternative path method is used to check if the structure is capable of bridging over a missing structural element, with the resulting extent of damage being localized. Three analysis procedures may be used, i.e. linear static, nonlinear static and nonlinear dynamic. The investigated mechanical properties of materials should be applied in the above analysis procedures. The load combinations are derived based on the expected service life of the structure. Some requirements, such as: (1) the type, location and size of the removed load-bearing elements, (2) the failure criteria for the structural elements, and (3) the damage limit for the structures, follow the provisions in the criteria (DoD 2005).

Finally, based on the above information comprehensive evaluation conclusions can be made. The conclusions are also contributed to the further structural retrofitting and strengthening.

Case Study

The proposed method is illustrated by means of a case study of a steel frame historic building in Shanghai, China, namely the Bund 18 building.

Architectural and Structural Overview The Bund 18 building (Fig. 2), built in 1923, was designed by *Palmer & Turner Architects and Surveyors* and constructed by *Trollope & Colls, Limited Engineering Department*. The total floor area of the building is about 10,450m^2, with the building height of 53.1m. Now it is the Excellent Historic Building in Shanghai, belonging to the second-class protective category. In the original design the building was mainly used for office. But currently it was proposed to transform into a commercial building. Fig. 3 shows the plane view of the first floor.

Figure 2: Picture for the Bund 18 building

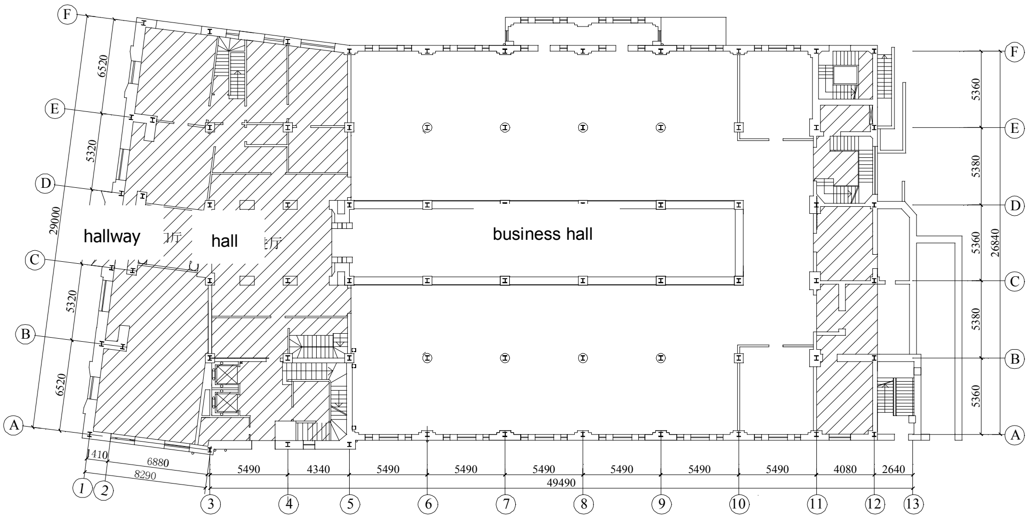

Figure 3: The plan view of first floor

There are five stories above the ground, consisted of cast-in-situ reinforced concrete slabs, steel I-beams with outside wrapped concrete as well as steel columns. The slab thickness is about 100mm. The columns are steel I-columns or in I-section bonded with steel plates, with masonry wrapped outside. Reinforced concrete beam-slab raft foundation is applied with short-piles underside. The beam-column joints can be handled as hinged ones because the steel beam are simply supported on the bracket of the columns. As a result, the supper structure of the building can be simply modeled as steel bent structure in lateral direction. It should be pointed out that such structural type is not usual according to modern design codes in China.

Evaluation of Building Layout Firstly, the roads around the building are straightforward and unobstructed, and the distance between building perimeter and the nearest roadside is about 5m, which does not meet the requirements (25m) in the relative criterion (DoD 2003). Secondly, there is no perimeter anti-ram barrier or explosion-proof wall around the sides of the building according to the retrofitting plan, which make it difficult to prevent a car bomb from breaking into the building. Thirdly, the parking lot is not located in the interior of the building, thereby can be mitigated the risk of structural damage caused by car bombs blast. Fourthly, no special protective measures were taken on the structural elements, so the elements do not have enough ability to prevent and resist blast.

Investigation of Geometrical Information, Structural Construction and Material Properties These information were investigated in detail using on-site inspection techniques or by tests in laboratory (SECoCETJ 2003). For example, Fig. 4 shows the stress-strain curve for a round steel bar specimen with the diameter of 8mm. The material properties are showed in Table 1.

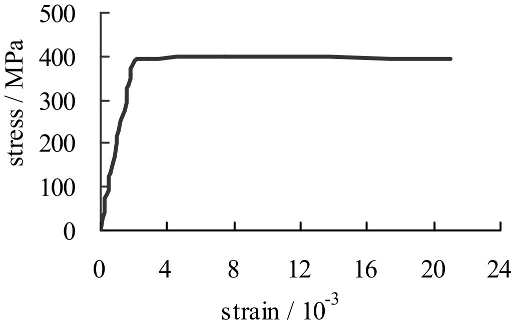

Figure 4: Stress-strain curve for a round steel bar with the diameter 8mm)

Table 1: Material properties

material	*location*	*strength(MPa)*	*remarks*
concrete	column in basement	30.6	carbonation depth: 4mm
	foundation beam of basement	29.0	carbonation depth: 39mm
	plate of first floor	32.1	carbonation depth: >30mm
	beam of first floor	17.9	carbonation depth: 55mm
	plate of third floor	21.6	carbonation depth: 67mm
	plate of fourth floor	21.4	-----
	beam of fourth floor	19.4	carbonation depth: 76 mm
	plate of fifth floor	16.6	carbonation depth: >31 mm
	Plate of roof	34.9	carbonized completely
round steel bar	lintel in basement	413	diameter 7.5 mm, yield strength
		288	diameter 11.3 mm, yield strength
steel plate	steel column in basement	287	ultimate strength, chemical component: 15%C, 62%Mn, 5.6%P, 4.1%Si
	steel beam in basement	287	ultimate strength, chemical component: 17% C, 61%Mn, 3.0%P, 6.4%Si

Tie Force All types of tie forces are calculated based on the investigated results and listed in Table 2. It can be seen that the constructions of the building meet the requirements in DoD (2005).

Table 2: Calculated results of tie forces

tie force types	internal	peripheral	external column	corner column	vertical
calculated results (kN)	1075	1075	1327	1075	2412
meet requirements or not	YES	YES	YES	YES	YES

Alternate Path Method The computational model is shown in Fig. 5, using finite element method based computer program SAP2000. Column A1, A7, C1 and C6 on the first floor and column A7 on fourth floor were to be removed respectively. Nonlinear static analysis procedure was applied to evaluate the performance of this structure to resist progressive collapse. The expected service life of this structure was assumed the same as the design reference period (50 years). The design strength of materials f_d was calculated using Equation (1) (MoHURD and GAoQSIQ 2005),

$$f_{\mathrm{d}} = \gamma_{\mathrm{d}} f \tag{1}$$

where f means the investigated material strength under static load, and γ_{d} means the comprehensive adjustment factor for material strength under dynamic load.

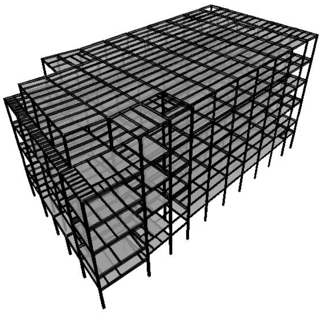

Figure 5: The computational model

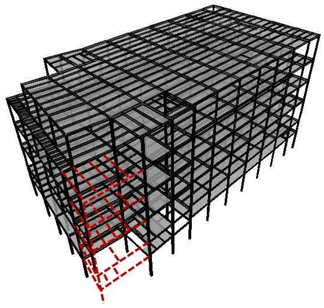

Figure 6: Collapse due to removal of column A1

Fig. 6 shows the collapse of the structure caused by removal of column A1 in first floor. The collapse areas for the abovementioned five removal cases were listed in Table 3. It was showed that no progressive collapse occured according to the damage limit of structure addressed in DoD (2005). The structure inclined to collapse from the roof to the first floor, localized only in the span containing the removal column. This is because the structural connections are all regarded as hinged joints, which makes it difficult for the loads to transfer horizontally and thus for the damage to develop to the adjacent spans.

Table 3: Collapse areas for five removal cases

removed columns	A7 (1st floor)	C1 (1st floor)	A1 (1st floor)	C6 (1st floor)	A7 (4th floor)
collapse areas(m^2)	58.9	0	51.7	117.9	58.9

Evaluation Results Based on the above analysis, the following conclusions can be drawn: (1) the building layout is not reasonable enough to prevent bomb place and to protect occupants from a potential disaster effectively, (2) the structural construction meet the requirements of tie force method, (3) the structure performs well in resisting progressive collapse according to alternative path method.

Suggestions: (1) increasing the standoff distance appropriately. If the actual conditions are impossible to do this, barriers such as fences, stairs and other obstacles may be set at the entrance of the building, (2) taking protective measures such as using explosion-proof glass for windows, setting high-strength fabric on the inside of the external walls of the building. These measures may prevent the occupants from explosion fragments effectively.

Concluding Remarks

Progressive collapse evaluation is a part of the protection work for historic building structures. The comprehensive evaluation process includes the aspects related to building layout, investigation of geometrical information/structural constructions/material properties, design approaches etc.. The development of all kinds of detection techniques and design theory will help to improve the accuracy and objectivity of the evaluation for structures to resist progressive collapse.

Acknowledgments

The authors gratefully acknowledge the financial supports provided by National Key Technology R&D Program under No. 2006BAJ03A07 and Shanghai Pujiang Program under No. 07pj14084.

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