Engineering Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Numerical investigations on static and dynamic responses of reinforced concrete sub-assemblages under progressive collapse

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Reinforced concrete
Progressive collapse
Catenary action
Sub-assemblage
Blast load
Numerical model

ABSTRACT

To study the effect of blast pressure on structural resistance against progressive collapse under column removal scenario induced by contact detonation, and to investigate the development of catenary action within ultra-fast dynamic regime, a physics-based finite element model is developed in this paper. The model is first validated by a quasi-static test series on reinforced concrete sub-assemblages under middle column loss assumption and a blast test series using the same structural configurations. The sub-assemblage included a two-span beam, a middle column stub and two column stubs at both sides. Besides validations with sub-structure tests, some pull-out tests are also performed to verify the numerical models. After the verifications, parametric studies are conducted to investigate the influence of important dynamic and structural factors such as the boundary stiffness, damping ratio, and charge weight attached to the middle column. The study shows that under actual blast conditions, catenary action in sub-assemblages can be mobilised to prevent a structure from collapse even when the bottom longitudinal reinforcement in the bridging beam has already fractured. Moreover, stiffness of horizontal restraints plays an important role to mitigate disproportionate collapse in both static and blast conditions. A comparison is also made between nonlinear dynamic procedure and nonlinear static analysis incorporating simplified energy method for dynamic assessment. It is concluded that the simplified static approach in lieu of dynamic analysis can be considered as a conservative method for practical design purpose. Nonetheless, this method may over-estimate structural resistance if the localised damage is induced by a contact-detonation event.

1. Introduction

The risks of progressive collapse on government and civilian buildings have been substantially increased nowadays due to heightened danger for terrorist attacks. Several methods and design guidelines have been released to help engineers to design structures against progressive collapse. Among them, direct method using Alternate Load Path (ALP) approach is an effective means to investigate structural resistance to progressive collapse [1,2]. However, its main assumption consisting of single-column removal scenarios, has often been criticized as un-realistic [3] due to the neglect of initial damages from the blast event. Suffice to say, ALP is a threat-independent approach.

Due to the complexity and extensive resources required for nonlinear dynamic analysis, performance-based approach is less preferred for investigating structural response under progressive collapse scenarios. Instead, a nonlinear static procedure incorporating equivalent dynamic factor is usually preferred in practice. Dynamic effects can be considered through load-increase factors [1,2] or by using simplified methods based on energy balance [4]. Although such kind of analysis is computationally efficient, it needs to be verified by actual blast tests.

Recently, there have been extensive experimental studies on ALP approach of reinforced concrete (RC) structures [5–8]. Most of them apply quasi-static method to investigate structural responses against progressive collapse situations. The mobilisation and development of both compressive arch action and catenary action, which strongly depend on lateral restraint conditions, were clearly observed. While compressive arch action is an efficient way to enhance the maximum flexural capacity of the beam section, catenary action can be considered as the last safety net to prevent the structure from complete collapse. Nonetheless, the capacity of catenary action under ultra-fast dynamic (blast) regime has not yet been confirmed experimentally.

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http://dx.doi.org/10.1016/j.engstruct.2016.07.042
0141-0296/

Please cite this article in press as: Pham AT et al. Numerical investigations on static and dynamic responses of reinforced concrete sub-assemblages under progressive collapse. Eng Struct (2016), http://dx.doi.org/10.1016/j.engstruct.2016.07.042

Due to exorbitant cost and safety issues, only very limited number tests on RC structures have been conducted under blast conditions. Instead, numerical simulations are normally preferred for investigating structural response and failure modes under such threats. In terms of static condition, finite element method (FEM) using simplified components such as fibre beam elements or component-based joint models can be applied to save computational cost [7,9]. However, when actual blast effects are considered, physics-based models using solid elements with sophisticated constitutive laws for materials are usually employed [10]. To study the development of catenary action under both quasi-static and dynamic regimes, and to quantify the effect of blast loads on RC structures caused by contact detonation, numerical analyses using physics-based FEM are developed and presented in this paper. Results from the study confirm the enhancement of catenary action in preventing collapse, which has not been clearly observed in previous blast tests [11]. Several important factors which significantly affect the mobilisation of catenary action are considered. The research concludes that the simplified frame-work on dynamic assessment proposed by Izzuddin et al. [4] gives acceptable predictions in comparison with the actual tests when the combined effects of damping and blast are neglected.

2. Numerical validations on beam-column substructures

2.1. Quasi-static and contact-detonation tests on RC sub-assemblages under column removal scenario

A quasi-static experimental programme on progressive collapse resistance of beam-column sub-assemblages with the middle column "removed" was conducted in 2010 at Nanyang Technological University [7,8] and the test results are used to validate numerical models developed in this study. Detailed information of the test data is described in the report [12]. The structure consisted of a two-span beam with a middle joint and two column stubs on each end as shown in Fig. 1. Removal of the supporting column was simulated by slowly increasing the displacement of the middle joint using a vertical actuator. The test series included eight specimens, named S1–S8. The first six specimens had the same geometry but different reinforcement ratios and arrangement, whereas the last two (S7 and S8) had different beam-spans. To represent translational and rotational restraints of the end joints, one roller support and two horizontal restraints were placed at each column-stub. Among the eight specimens, results from the first seven tests showed significant improvement of catenary action on structural behaviours. Whereas in the last specimen, S8, catenary action had almost no effect on structural capacity due to its small span-depth ratio and the specimen was severely damaged under shear failure. Rebar detailing and material test of all specimens are presented in Tables 1 and 2, while Fig. 1 shows the configuration of the test.

To investigate the effects of ultra-fast dynamics compared to quasi-static loading regimes, a series of progressive collapse tests induced by contact detonation was conducted at Fraunhofer EMI, Germany in 2012 [11]. The specimen design and boundary conditions were similar to specimen S2 from the static tests conducted at NTU. Column removal was simulated by detonating a C-4 charge placed at the middle column of the specimen. Specimen design and general configuration of the contact detonation tests are shown in Figs. 2 and 3, respectively. Two test results, i.e. SD-2 and SD-3, are used in this paper to validate the proposed FEM models. These two specimens had similar design, test setup and charge weight placed at the bottom of the middle column. The vertical applied loads on the middle column were 27 kN and 47 kN for SD-2 and SD-3, respectively. The results from the first specimen, SD-1, were not so reliable due to inappropriate ground fixing of the two massive restraints (Fig. 3) which led to a shift of these buttresses during the blast process. Hence, SD-1 is not considered in the present study.

Test results of specimen SD-2 showed that, after the middle support was removed by blast pressure, the middle joint experienced uplift within the first 100 ms before falling freely under gravity load and finally sustaining a residual deflection of 50.2 mm. With an imposed load of 27 kN, the response of SD-2 followed a flexural manner with the appearance of compressive arch action (denoted by the mobilisation of horizontal forces at the two end supports). Compared to SD-2, SD-3 with a larger imposed load of 47 kN responded beyond the maximum compressive arch action capacity. Displacement of the middle joint kept increasing until the specimen hit the ground at 471.7 mm. The horizontal reaction of SD-3 was compression at the beginning but switched to tension when the middle joint deflected more than one beam-depth, indicating the contribution of catenary action before the specimen hit the ground. From the test, it was not clear whether SD-3 had failed or could still sustain the applied load of 47 kN if there was ample headroom for deflection.

2.2. Numerical model

From a previous study of the authors [7], component-based models using fibre-based beam elements have been employed to simulate the structural response, which was shown to be computationally efficient compared to 3D solid elements used in the current paper. This simplified numerical analysis is helpful for engineers to quickly evaluate the overall static response of sub-assemblages under column removal scenarios. On the other hand, the 3D physics-based models used in this study is more complicated to employ and more time consuming, but can provide a more detailed structural response, e.g. graphical damage patterns of concrete, physical fracture of rebars. Most importantly, it is able to simulate dynamic responses under blast effects, which cannot be performed using the simplified beam models.

An explicit finite element software LS-Dyna [13] is used to simulate the sub-assemblage tests due to its numerical stability, as well as a wide variety of available constitutive models. Based on the assumption of symmetry for loading, geometry, boundary conditions and material properties from the test, only one-half of the specimen is modelled as shown in Fig. 4. Concrete is simulated using 8-node solid elements with reduced integration scheme. Reinforcing bars are explicitly modelled by 2-node Hughes-Liu

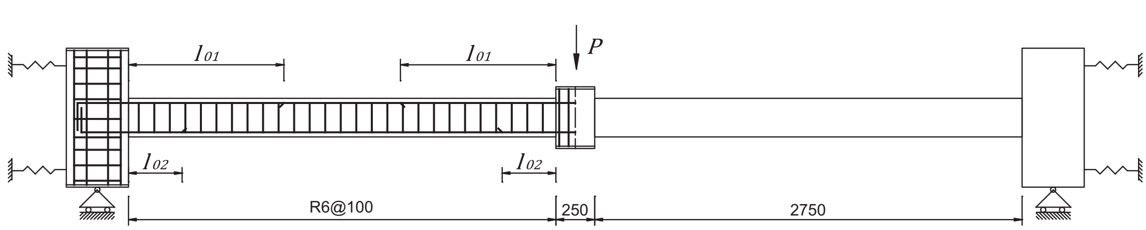

Fig. 1. Test setup [7,8].

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