Engineering Structures 110 (2016) 293–306

Contents lists available at ScienceDirect

Engineering Structures

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

An approach for evaluating residual capacity of reinforced concrete beams exposed to fire

V.K.R. Kodur *, Ankit Agrawal

Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States

A R T I C L E I N F O

Article history:
Received 15 May 2015
Revised 16 November 2015
Accepted 18 November 2015
Available online 29 December 2015

Keywords:
Reinforced concrete beams
Residual strength
Finite element analysis
Fire exposed beams
Residual deformations

A B S T R A C T

This paper presents an approach for assessing the residual capacity of fire exposed reinforced concrete (RC) beams. The approach involves capturing response of RC beams in three stages, namely, structural response at ambient conditions, thermo-mechanical response during fire exposure, and post-fire residual response after cooling down of beams. Distinct material properties of reinforcing steel and concrete are considered during heating and cooling phase of fire exposure and residual (after cool down) phase of analysis. In addition, relevant load level, specific fire scenarios, boundary conditions, and plastic deformations that develop in a beam during fire exposure are also incorporated in evaluating residual response of fire exposed RC beams. The proposed approach is implemented using a detailed numerical model developed in the finite element computer program ABAQUS. Predictions from the numerical model show good correlation with the response parameters measured in experiments for evaluating residual capacity of fire exposed RC beams. Also, predictions of residual capacity from the finite element analysis are compared with that obtained from simplified sectional analysis based on maximum rebar temperatures consideration. This comparison indicates that the finite element analysis yields more realistic predictions of residual capacity than that predicted from simplified sectional analysis. The applicability of the proposed approach in evaluating residual capacity of fire exposed RC beams is illustrated through a case study.

1. Introduction

Reinforce concrete (RC) structural members generally exhibit good fire resistance due to relatively low thermal conductivity, high thermal capacity, and slower degradation of mechanical properties of concrete with temperature. However, under fire exposure, RC members experience loss of strength and stiffness as a result of increased temperatures in reinforcing steel and concrete.

In case of exposure to a severe fire, a RC member might experience significant structural damage resulting from loss of concrete due to possible fire induced spalling, high rebar temperatures and relatively large permanent deformations with very limited residual load carrying capacity. Alternatively, exposure to moderate fire scenarios may not result in noticeable deformations or loss of concrete section due to spalling. In such scenarios, loss of capacity in RC structural members due to fire exposure may not be significant. Nevertheless, a fire exposed building (or structure) cannot be opened for immediate reoccupation, even after fire is fully extinguished, until load bearing capacity of RC members are ascertained. Unlike fire induced spalling and significant loss of cross section, which is a visible sign of damage, structural deterioration in a RC member due to temperature induced degradation of mechanical properties and redistribution of stresses within the member, may not be too apparent. Thus, it is imperative to ascertain the residual capacity of structural members through rational engineering methods for facilitating re-occupancy or to develop retrofitting measures in fire exposed concrete buildings.

The extent of strength and stiffness degradation in fire exposed concrete members is dependent on a number of factors, including type of fire exposure, properties of concrete and steel reinforcement, load level and boundary (support) conditions. Many of these factors are interdependent and can vary significantly in different scenarios. Thus, residual strength evaluation of fire exposed RC members is quite complex and the computed capacity can vary widely depending on assumptions used in the analysis.

One approach to evaluate residual capacity of RC members is through destructive fire tests in a laboratory environment. Such residual capacity tests have been conducted in the past by researchers [1–5] and this comprised of exposing RC beams to standard or parametric fires for a predetermined duration, and then loading the beams to failure after cooling down to room temperature, if no failure occurred during fire exposure. Common

* Corresponding author. Tel.: +1 5173539813.
E-mail addresses: kodur@egr.msu.edu (V.K.R. Kodur), agrawa36@msu.edu (A. Agrawal).

http://dx.doi.org/10.1016/j.engstruct.2015.11.047
0141-0296/

observations from these tests inferred include that significant residual load carrying capacity remained in these members and the extent of residual capacity varied with the duration of fire exposure and peak rebar temperature.

Researchers have proposed nondestructive or numerical approaches for evaluating residual capacity of RC beams following fire exposure [6–8] as well. These approaches can be broadly categorized into two types, namely, simplified cross-sectional analysis and, detailed finite element analysis. In the first type of approach, modified versions of strength equations for evaluating capacity at room-temperature are utilized accompanied with strength reduction factors based on high temperature exposure.

Hsu and Lin [6] proposed a simplified sectional approach to evaluate residual strength of fire exposed RC beams. This approach involves dividing critical cross section into a number of strips and then calculating temperatures along each strip through a finite difference approach. Knowing temperatures across the cross section and strength-temperature relations of reinforcing steel and concrete, residual capacity of the fire exposed concrete beam is evaluated through a strain compatibility analysis. They concluded that this approach could be applied to calculate post-fire moment capacity, shear strength and elastic modulus of an RC beam. Also, the rate of degradation in moment capacity, shear strength and elastic modulus were different.

Kodur et al. [7] presented a simplified approach for evaluating residual capacity of flexural members based on peak rebar temperatures experienced during a fire. As part of this method, an empirical equation was proposed for predicting maximum rebar temperatures under a specified parametric fire exposure. Knowing maximum temperatures attained in the rebar, residual capacity was computed using modified versions of room-temperature strength design equations [9], but taking into account residual properties of reinforcing steel. It was shown that the proposed approach gives conservative predictions of residual moment capacity of a fire damaged RC beam. Peak rebar temperature was identified as the key parameter in ascertaining the level of damage sustained to the beam during fire exposure.

In a more recent study by Bai and Wang [8], maximum temperatures across the cross section are evaluated using ANSYS [10] software. In this approach, instead of assuming degradation in the strength of concrete or steel reinforcement with increasing temperature, the original section of concrete and rebar is reduced to an equivalent (reduced) section to account for damage due to fire and then post-fire residual capacity of RC members is evaluated. Based on this study it was inferred that concrete or steel strength has negligible influence on the rate of degradation in moment capacity due to fire exposure.

In the second type of approach, researchers utilize a finite element model to trace the post-fire response of RC beams. Ožbolt et al. [11] have proposed a transient three dimensional thermo-mechanical finite element model to simulate the behavior of RC beams exposed to elevated temperatures. The model was validated by comparing predictions against test data generated from post-fire residual strength tests [2]. The load-carrying capacity and the initial stiffness of the beam reduced with the increase in duration of fire exposure. Moreover, it was found that on cool down of the beam to room temperature, additional damage resulted in the beam due to thermally induced strains.

A major drawback of the approaches proposed by Hsu and Lin [6] and Bai and Wang [8] is that these approaches utilize temperature induced degradation of mechanical properties of concrete and reinforcing steel evaluated based on heating phase alone. However, such properties are not representative of those observed (residual mechanical properties) after cool down following fire exposure. While concrete continues to display some level of strength loss even after cooling down [12], reinforcing steel regains most of its room temperature strength if maximum temperature experienced during fire exposure remains below 500 °C [13]. Also, most of the cross-sectional residual capacity evaluation approaches discussed above do not account for strain hardening effects in reinforcement, which can lead to under-prediction of moment capacity by 15–25% than the actual value experienced in real practice [7]. It is not possible to predict post-fire residual deformations in RC beams through the current sectional approaches. Finally, the model proposed by Ožbolt et al. [11] does not account for distinct material properties during heating and cooling (decay) phases of fire. Moreover, the primary focus of the study was to study behavior of RC beams at elevated temperature rather than evaluation of post-fire residual capacity of RC beams.

To overcome some of the above drawbacks, an approach is proposed for predicting residual capacity and residual deflections of fire exposed RC beams. The novelty of the current approach lies in the consideration of distinct material properties of reinforcing steel and concrete during heating and cooling phases of fire exposure and residual (after cool down) phase, as well as in incorporation of plastic deformations occurring during fire exposure of RC beams into post-fire response analysis. The proposed approach is implemented through a detailed numerical model developed in a finite element based computer program ABAQUS [14]. The model is validated by comparing predictions against experimental data generated in residual strength tests on RC beams [2,3]. Finally, the numerical model is applied to evaluate post-fire residual response of fire exposed simply-supported, unrestrained, rectangular RC beams.

2. Approach for evaluating post-fire residual capacity

The extent of structural damage in a fire exposed RC beam is influenced by a number of factors including load level, support conditions, properties of concrete and reinforcement as well as fire exposure scenario [7]. For evaluating post-fire residual response of RC members, three stages of analysis are required to account for all these parameters.

2.1. General procedure

The three stages of analysis for evaluating residual capacity of fire exposed RC members comprise of, evaluating capacity at room temperature prior to fire exposure (Stage 1), fire resistance analysis during exposure to fire (Stage 2) and finally, post-fire residual analysis after cooling down of the member (Stage 3). A flow chart in Fig. 1 illustrates various steps required for evaluating residual strength of fire exposed RC beams. This analysis procedure can be implemented using any finite element based package, such as ABAQUS [14].

In Stage 1, room temperature capacity of the RC beam is evaluated through a detailed finite element analysis by gradually incrementing the load on the structure till failure occurs. Alternatively, the ultimate capacity can also be estimated using specified strength equations in design standards [9]. The room temperature capacity determined in Stage 1 is utilized to assess relative load level on the beam prior to fire exposure during Stage 2. Also, the capacity calculated during Stage 1 is used to estimate extent of degradation in capacity once the residual capacity is ascertained in Stage 3. It should be noted that for this stage of analysis, room temperature mechanical properties of concrete and reinforcing steel are utilized.

In Stage 2 of the analysis, the response of RC beam is evaluated under a given fire exposure scenario, load level, and boundary conditions. Realistic loads that are present throughout a typical fire event are applied on the beam prior to thermo-mechanical analysis