Engineering Structures 87 (2015) 153–161

Contents lists available at ScienceDirect

Engineering Structures

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

Yield design-based analysis of high rise concrete walls subjected to fire loading conditions

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ARTICLE INFO

Article history:
Received 6 June 2014
Revised 13 January 2015
Accepted 14 January 2015
Available online 11 February 2015

Keywords:
High rise walls
Reinforced concrete
Fire loading
Yield design approach

ABSTRACT

Relying on a simplified one dimensional beam-like schematization of the problem, a yield design-based approach is developed for analyzing the potential failure of high rise walls (that are larger than the dimensions of experimental test furnaces) under fire conditions. The implementation of the method combines two original features: first, the preliminary determination of interaction diagrams reflecting the local decrease in strength of the wall due to thermal loading; second, the thermal-induced geometry changes which are explicitly accounted for in the overall failure design of the wall. Application of the approach is illustrated in either evaluating the fire resistance of a wall of given height or predicting the maximum height that the wall could reach for a prescribed fire exposure time. First results of this analysis point to the conclusion that wall failure due to fire loading is highly sensitive to its height.

1. Introduction

Assessing the ultimate load bearing performance of reinforced concrete members subjected to fire exposure, and devising appropriate design methods, have been the subject of an increasing number of contributions in the last decades (see among many others Lie and Celikkol [1], Lie and Irwin [2], Dotreppe et al. [3], Franssen and Dotreppe [4] or El Fitiany and Youssef [5]). Quite recently, attention has been more specifically focused on the determination of axial force-bending moment interaction diagrams of a reinforced concrete section subjected to a fire induced temperature gradient (Caldas et al. [6], Law and Gillie [7]). The yield design approach in particular and its related lower and upper bound methods (Chen [9], Salençon [10]) have proved to be a suitable framework for determining such interaction diagrams in a rigorous way, either under ambient temperature (Averbuch [11], Koechlin and Potapov [12]), or when subjected to a temperature gradient (Pham et al. [13]).

Increasingly involved in the construction of tall industrial buildings, high rise concrete walls are large size reinforced concrete structures for which the evaluation of the fire resistance requires a more sophisticated approach than for conventional, *i.e.* smaller size structures. Indeed, the sole degradation of the stiffness and strength properties of reinforced concrete due to severe temperature increase, cannot explain as such the collapse of these structures. Due to the thermal-induced deformations, such slender structures exhibit important out-of-plane (horizontal) displacements, which in turn lead to an eccentricity of the gravity load (self-weight) with respect to the initial undeformed configuration. As a consequence, bending moments are generated in the wall in addition to the pre-existing compressive axial force distribution, which is usually known as a second order (or P-delta) effect (see for instance the classical textbook by Bazant and Cedolin [14]). As the eccentricity increases, the moment due to self-weight eccentricity also increases, thus subjecting the wall to higher bending moments and associated curvature deformations. At the same time, but independently, elevated temperature leads to a degradation of constituent materials. Consequently, it is the conjunction of fire-induced material strength degradation with developing bending effects which may trigger the overall failure of the structure, even before the occurrence of any buckling phenomenon.

The purpose of the present contribution is to extend the range of application of the yield design approach (Salençon [10]) in order to analyze the global stability of high rise walls, taking the geometry changes induced by the thermal loading into account. This contribution will demonstrate how it is possible to combine the global deformed configuration analysis with that of the local cross-sectional strength degradation. Unlike most of the classical

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http://dx.doi.org/10.1016/j.engstruct.2015.01.022
0141-0296/

approaches which are based on conventional limitations of the strains undergone by the concrete material and reinforcing steel, the yield design approach only requires that stress (and not strain) limitations be assigned to the constituent materials in the form of a strength or failure criterion, with no consideration for other material properties, such as for instance the elastic stiffness characteristics. From a fundamental viewpoint, the yield design (or limit analysis) reasoning is based on verifying the compatibility between static equilibrium of a structure subjected to given loading conditions in a defined geometric configuration, and strength conditions expressed through the above mentioned materials failure criteria, thus avoiding to perform computational time consuming incremental calculations.

The main original feature of the present approach lies in the fact that the geometric configuration of the high rise wall on which the yield design approach is to be performed, is not known *a priori*, but should be determined from a preliminary thermo-elastic calculation accounting for geometrically non-linear second order effects. The paper is thus organised as follows. Section 2 describes the simplified one dimensional beam-column model adopted for the high rise wall, the corresponding problem statement and the three-step procedure employed for solving the latter. Section 3 is devoted to a detailed presentation of step n°1 of the procedure, consisting in predicting the thermal-induced deflected configuration of the beam-wall, by means of a non-linear thermo-elastic analysis. Section 4 essentially relies on the results of a previous paper (Pham et al. [13]) making it possible to evaluate the local decrease of the bearing capacity of reinforced concrete sections in the form of temperature-dependent interaction curves (step n°2). Section 5 is concerned with the implementation of the last step, aggregating the results of the two previous steps, resulting in a final illustrative application of the whole procedure presented in Section 5.

2. Problem statement and outline of solution procedure

The problem under consideration is the potential instability or failure of a high rise reinforced concrete wall subjected to its own weight on the one hand and to fire exposure on the other hand. In the following, the boundary conditions on the lateral sides of the wall are prescribed in such a way that it can be simply modelled as a one dimensional vertical beam as sketched in Fig. 1.

The beamlike wall is uniformly exposed to fire on one side as well as to its self-weight. Following the standard curve of temperature versus time advocated by design codes [15] for modelling the action of a fire on a structure, a heat transfer analysis may be firstly carried out on the wall. In the case of a simple wall member such as that considered here, one-dimensional heat propagation across the wall thickness suggests that the field of temperature increase resulting from such a thermal loading will depend on the thickness-coordinate only.

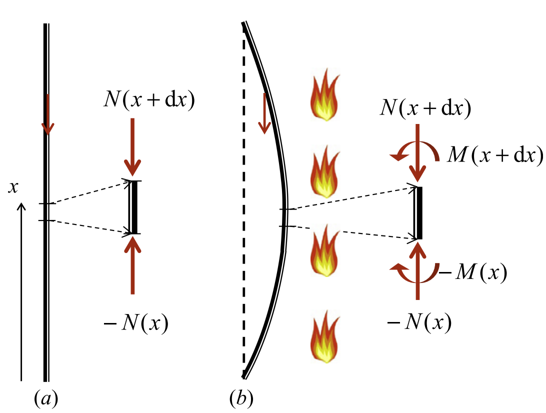

Fig. 1. Schematic diagram of a high rise wall subjected to fire loading: (a) initial and (b) deformed configurations.

Fig. 1 provides a first insight into the basic mechanism which may explain why failure of a high rise wall under fire loading may occur. In its initial configuration, that is prior to fire loading, the wall is a straight vertical beam subjected to its own vertical weight, resulting in a linearly increasing distribution of axial compressive force N along the wall (Fig. 1(*a*)). The wall is generally designed so as to avoid any buckling phenomenon, while the maximum compressive force at its base remains far below the compressive strength of the reinforced concrete section. As it will be explained later on in more details, the transverse gradient of temperature due to fire exposure on one side of the wall will induce a uniform thermal curvature of the beam and, as a direct consequence, out of plane transversal displacements will appear, leading to a deformed configuration of the wall (Fig. 1(*b*)). Under such conditions, simple equilibrium considerations imply that any wall cross section is subjected to a significant bending moment M in addition to the already existing axial compressive force N.

Apart from this first decisive phenomenon which could be attributed to an overall structural change of geometry (second order effect), experimental evidence clearly shows that the severe temperature increases associated with fire exposure, lead to an important degradation of the stiffness as well as strength properties of the reinforced concrete materials, namely plain concrete and steel reinforcements. It is the combined effect of these two phenomena (change of geometry on the one hand, decay of the material properties on the other hand) which may trigger the overall failure of the high rise wall.

The calculation and design procedure proposed and developed in this paper is derived from the implementation of the above considerations and their formulations in a rigorous and mechanically consistent framework. The analysis is performed in three main successive steps.

- Step n° 1. *Determination of the wall deformed configuration and generalized stress distribution*. This step consists first in evaluating the equilibrium configuration of the wall under the combined action of thermal gradient and self-weight, then in calculating the resulting local solicitations (axial force and bending moment) in each section.
- Step n° 2. *Determination of temperature dependent interaction diagrams*. The objective of this phase, which is completely independent from the first one, is to determine the axial force-bending moment yield strength capacities of any wall cross-section as a function of the prescribed temperature gradient.
- Step n° 3. *Yield analysis and design of the wall* in its deformed configuration determined in step n°1, on account of its reduced strength properties evaluated in step n°2.

The whole calculation procedure is sketched in Fig. 2.

3. Step n° 1. Thermal-induced equilibrium configuration

As mentioned earlier, the whole procedure is performed on a simplified one dimensional model of the wall, schematized as an initially straight vertical beam of height H, articulated at both ends as shown in Fig. 3, the bottom end being kept fixed, while the top end is free to translate vertically. The wall is subjected to its self-weight characterized by a constant linear density w and a uniform temperature gradient along its height, resulting in a preliminary deformed shape of equation $u_\theta(x)$, where u denotes the transversal displacement. This thermal-induced change of geometry implies an out-of-plane eccentricity of the self-weight and then additional elastic bending deformations, resulting in a new equilibrium deformed shape of equation $u(x)$.