Engineering Structures 177 (2018) 630–640

Contents lists available at ScienceDirect

Engineering Structures

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

A simplified non-linear structural analysis of reinforced concrete frames with masonry infill subjected to seismic loading

Peter B.K. Mbewe[a,*], Gideon P.A.G. van Zijl[b]

[a] Faculty of Built Environment, University of Malawi, The Polytechnic, Private Bag 303, Blantyre 3, Malawi
[b] Department of Civil Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

ARTICLE INFO

Keywords:
Ductility
Modified stiffness
Infill frames
Pushover analysis
Truss analogy

ABSTRACT

Structural performance of both new and existing building structures under seismic actions can be assessed with a wide range of nonlinear static procedures and time history dynamic analysis available in literature. Most of these procedures, such as time history dynamic analysis, are complex as they require sophisticated finite element modelling. Reinforced concrete (RC) frames with masonry infill, for example, pose great challenge in modelling both the composite material behaviour and their interactions. With significant effort directed towards sustainable infrastructure development, a simplified nonlinear analytical procedure for evaluation of RC infill frames subjected to incremental horizontal loading is developed that can be used easily in integrated structural performance and sustainability evaluation. The method, developed on the premise of truss analogy and utilising the pushover analysis, assumes that all structural members of the RC frame are truss elements with homogeneous material properties derived on the basis of a pure axially loaded system and the infill masonry is converted into strut elements. Stiffness modification through evaluation of nonlinear stress-strain states is employed to generate the overall force-deformation behaviour of the structural system. Experimental data available in literature is used to validate the procedure.

1. Introduction

Evaluation of the nonlinear seismic behaviour of RC frames with masonry infill that is typically conducted using either the incremental dynamic analysis (IDA) or nonlinear static procedures (NSPs). While an IDA procedure is complex and requires more computational efforts, NSPs, adopted for this paper, are typically less time demanding and require less computational efforts. Although simple push-over analysis is considered here, extension to cyclic analysis is possible, and would require incorporation of appropriate stiffness degradation and hysteresis behaviour. The use of macro-models, where the masonry infill is represented by an equivalent strut mechanism, has proved to be both viable and requires less computational efforts [1–4]. Current efforts towards sustainable infrastructure development would require use of appropriate structural system, structural topology and the structural materials that meet certain sustainability criteria. Thus, structural modelling procedures and seismic evaluation methods that generate reliable results and require minimal computational efforts would be ideal for promoting sustainability integration in structural performance evaluation. It is against this background that this paper proposes a simple method

for seismic evaluation of the RC frames with masonry infill that can easily be integrated with sustainability evaluation of structures. A truss analogy is adopted that considers the whole RC frame with infill as a truss system. Principles of static condensation and calibration of material parameters through parametric evaluation have been adopted to convert the frame into a truss, while the infill is represented by an equivalent strut mechanism. A single span single storey frame is used. However, the proposed method can be used for a multi-storey frame, where either incorporation of appropriate boundary conditions are used or appropriate material and geometric models are adjusted to use a full frame system as discussed in Section 3.4.

2. Evaluation of seismic capacity of infill framed structures

Macro-models, using equivalent struts, are widely used to evaluate the behaviour of the RC infill frames subjected to lateral loading [2,5–8]. NSPs are used to evaluate the nonlinear structural performance of building structures subjected to seismic loading [3,9–11] where adaptive pushover techniques are used to establish the capacity curves (defined as the relationship between the base shear and lateral displacement of a control node). Two key steps in estimating seismic demands in NSP can be summarised as: (1) estimation of the target node displacement; and (2) pushover analysis of the structure subjected to monotonically increasing lateral forces with specified height-wise

* Corresponding author.
E-mail address: pmbewe@poly.ac.mw (P.B.K. Mbewe).

https://doi.org/10.1016/j.engstruct.2018.10.005
Received 14 March 2018; Received in revised form 26 September 2018; Accepted 2 October 2018

distribution until the target displacement is reached [12]. While a typical structure may comprise of multi-bays and or multi-storeys, specific assumptions are employed with regard to nonlinear static analysis procedures for a multi-degree of freedom (MDOF) system, namely:

(a) Use of single degree of freedom (SDOF) oscillator to model an 'actual' system which is usually an MDOF; and
(b) Use of a predetermined load vector which is used to distribute load to various nodes for a multi-degree of freedom system using various methods such as equivalent linearization and displacement modification.

The existing NSPs use equivalent SDOF system and convert the response/lateral loads through various methods that are based on the assumption that the response is controlled by the fundamental mode and that the mode shape remains unchanged after the structure yields. The height-wise distributions of lateral loads for the pushover analysis can be performed using any of the four methods as discussed by Goel and Chadwell [12], namely: (a) equivalent lateral force distribution (b) fundamental mode distribution, (c) response spectrum analysis distribution and (d) uniform distribution.

2.1. Performance comparison of NSP

A comparison of peak roof (or target node) displacements estimated from the NSPs with the value derived from recorded motions conducted by Goel [13] showed that: (1) the NSPs either overestimate or underestimate the peak roof displacement for several of the buildings considered; (2) the ASCE-41 Coefficient Method (CM), which is based on recent improvements to the FEMA-356 [14] CM suggested in FEMA-440 document [15], does not necessarily provide a better estimate of roof displacement; and (3) the improved FEMA-440 Capacity Spectrum Method (CSM) [15]generally provides better estimates of peak roof displacements compared to the ATC-40 CSM. However, there is no conclusive evidence that either the CM procedures (FEMA-356) or the CSM procedure (ATC-40 or FEMA-440) lead to a more accurate solution. Various researchers have found that the CM and CSM may provide substantially different estimates of target displacement for the same ground motion and the same building [3,10,13,16] and have proposed improved procedures for estimating the target displacement. These discrepancies exist across various methods in spite of using complex numerical modelling in evaluation of NSPs [15].

2.2. Macro-modelling of RC infill frames

Most of the macro-models for the infill frames were developed based on the observed behaviour of the infill when subjected to lateral loading. Since most of these macro-models reflect some of the main failure phenomena for infill frames, the choice of the model and its geometrical and material characteristics may be dictated by the possible failure mode which is predicted before an extensive modelling of the structure is undertaken [1–3]. Dominant failure modes for the infill frame are corner crushing, diagonal compression, sliding shear, diagonal cracking and frame failure modes [17]. Equivalent struts such as single strut model, multi-strut model and multi-strut models with shear springs can be used for infill modelling. The key feature in these models is the determination of strut width, location of struts and material modelling [7,18–20]. In this paper, existing single strut models were reviewed [19,20], and used to generate the force-deformation (F-δ) characteristics that can be used in seismic assessment of the structures. The performance of the proposed model in terms of the F- δ characteristic is compared with experimental data available in literature.

The equivalent strut model allows the calculation of the stiffness of the infill frame and actions when subjected to lateral forces [21,22]. Evaluation of masonry resistance, as represented by the equivalent struts, has been one of the challenges in the equivalent strut modeling. The choice of appropriate strut widths and their corresponding material strength has been an issue of concern as there are are great deviations in the derivation of strut width and their corresponding material properties. These variations can be alluded to the fact that masonry panels have different modes of failure hence difficult to characterise its behaviour. Existing equivalent struts material models can represent both the elastic and inelastic behaviour of the infill [1,8,18]. Most of the existing models are used after conducting a pre-evaluation analysis that determines the potential mode of failure and hence the relevant strength and overall strut behaviour [2,23]. However, a new strut characterisation that does not require pre-evaluation analysis developed by Mbewe [23].

3. Proposed truss analogy for equivalent system evaluation

3.1. Frame to truss transformation

The geometric model for the infill frame is represented by a truss comprising the equivalent diagonal infill strut and a truss generated to represent the frame. The truss material models are based on both the infill strut and the frame-to-truss elements. The bare frame is converted to a truss by condensing the rotational DOFs to lateral DOFs [24], and representing the rotational resistance with a diagonal strut. A single bay single storey structure is used to develop an equivalent truss system for a frame structure. The structural frame is assumed to be axially stiff so that only the flexural stiffness contribution is considered when converting the frame to axial diagonal elements. Furthermore, no prescribed initial deformation due to the foundation subsidence or any other load effects is considered. Vertical translations, u_i, at nodes 2 and 3 are made to be zero, while nodes 1 and 4 are fixed for the frame system and pinned in the equivalent truss system (see Fig. 1). The global coordinates are represented by x, y axes while local coordinates are represented by x', y' axes. Appropriate DOFs, indicated in the local axes, are also shown in the figure. Each element's geometrical and material properties represented by the second moment of area (I_b, I_c) and length (L_b, L_c) and Young's modulus (E_c, E_b) are also indicated in Fig. 1. The subscripts b and c represent the beam and column properties respectively.

Considering stiffness that corresponds to nonzero DOFs and their respective forces, a force equation of the system is:

$$\begin{Bmatrix} P \\ 0 \end{Bmatrix} = \begin{bmatrix} k_{ff} & k_{fn} \\ k_{nf} & k_{nn} \end{bmatrix} \begin{Bmatrix} d_f \\ d_n \end{Bmatrix} \tag{4}$$

where k_{ff},k_{fn},k_{nn} and k_{nf} are assembled stiffness matrices corresponding to the unconstrained DOF, d_f, and constrained DOFs, d_n, for force P (unknown) and assembled stiffness matrices corresponding to the unconstrained DOF, d_f, and constrained DOFs, d_n, for force 0 (known) respectively.

Making P the subject of formula in Eq. (4), becomes

$$P = (k_{ff} - k_{nf}^{T} k_{nn}^{-1} k_{nf}) d_f \tag{5}$$

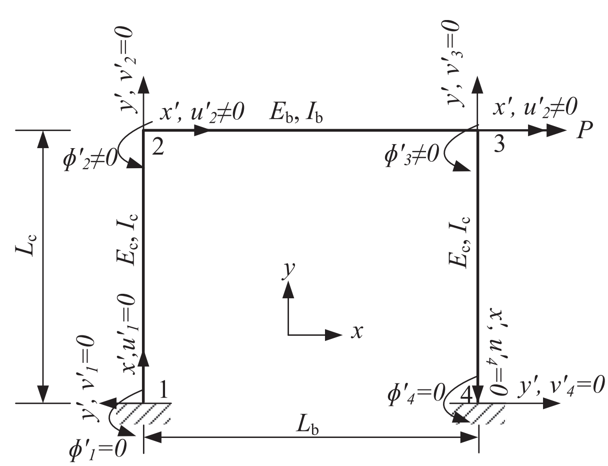

Fig. 1a. Condensation of a frame's flexural DOFs to lateral DOF, u_2.