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Approximate limit load evaluation of structural frames using linear elastic analysis

Claudia C. Marin-Artieda, Gary F. Dargush*

Department of Civil, Structural, and Environmental Engineering, State University of New York at Buffalo, NY 14260, USA

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Abstract

This work investigates applications and limitations of iterative modulus variation procedures combined with linear elastic analysis to calculate lower bounds of collapse loads. These modulus variation procedures are currently used to account for inelastic behavior in pressure vessel and piping system design. Here, applications to framed structures are studied. Three different modulus variation procedures are implemented within a conventional linear elastic finite element code and compared. The procedure that reduces only elastic moduli at high stressed elements of a structural model is found to be the most convenient strategy to estimate collapse conditions. This procedure is then applied to two- and three-dimensional frames, with homogeneous and non-homogeneous cross-sections, and assuming both constant and proportional loading. Using this procedure, it is possible to predict satisfactory approximations of collapse loads and failure mechanisms. In earthquake engineering practice if the earthquake motions are simulated as equivalent static proportional loads, this simplified procedure may be a useful and economical tool in the implementation of performance based design procedures in preliminary engineering, in verification processes, in structural optimization, and when facing complex geometric configurations. This procedure can be used to estimate approximations of both load redistribution in collapse conditions and failure modes when assuming different lateral load patterns along with gravity loads. It can be useful to determine optimum failure modes in new structures or weak links in existing structures. The method requires only minimal conceptual bases for application and moderate computational effort.

Keywords: Collapse loads; Failure modes; Linear analysis; Moduli reduction; Frames; Lower bound analysis

1. Introduction

This work investigates both the applicability and limitations of conventional linear elastic analysis combined with iterative modulus variation to calculate lower bounds of collapse loads and collapse mechanisms in framed structures.

In engineering design, simplified procedures are used to account for nonlinear behavior when only linear elastic analyses are available. For example, in piping systems design, repeated elastic finite element analyses with special variation of the elastic modulus are performed to simulate a variety of inelastic behavior such as: local inelastic strains, limit loads, shakedown loads, and other inelastic parameters. These procedures, referred to herein as Modulus Variation Procedures (MVP), are currently recommended for pressure vessel design by the American Society of Mechanical Engineers, by European guidelines, and are being studied by the Japanese Society of Mechanical Engineers.

MVP are based on the assumption that local inelastic behavior can be simulated by lowering the elastic modulus at the high stressed elements of a structural model. MVP are attractive because they require only minimal conceptual bases for application and moderate computational effort to obtain satisfactory approximations of failure mechanisms and collapse loads for relatively complex structures. Although recent research has improved the understanding of nonlinear behavior, and sophisticated computer software has made nonlinear analyses more accessible, it is not yet routine to perform a reliable nonlinear analysis in design practice. In fact, a nonlinear analysis requires a proper model definition; a lack of knowledge or a misunderstanding of the nonlinear behavior may lead to the wrong conclusions. Thus, in engineering

* Corresponding author. Tel.: +1 716 645 2114x2405; fax: +1 716 645 3733.
E-mail addresses: ccm6@buffalo.edu (C.C. Marin-Artieda), gdargush@eng.buffalo.edu (G.F. Dargush).

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practice, simple procedures are welcome in preliminary estimations and in verification processes.

This paper begins with a brief summary of the literature on MVP for simulating inelastic response. MVP are organized here into three categories: (i) the original MVP called herein Reduced Elastic Modulus Procedure (REMP); (ii) the Generalized Local Stress Strain Analysis (GLOSS analysis), with a sub-procedure called the R-node method, and (iii) the Elastic Compensation Method (ECM). Then MVP are employed to estimate collapse loads using a one-degree-indeterminate beam. By assigning two different elastic moduli for this beam, it is possible to obtain the exact collapse load and the failure mechanism. Later, the REMP, the R-node method and the ECM are implemented in a finite element code to calculate the collapse conditions for simple plane frames; after this attempt, the REMP is recommended over the other methods. The REMP uses automatic commands of a conventional linear elastic finite element code with an iterative modulus reduction based on a yield criterion that is applied at the high stressed elements of the model. At present, this procedure does not include second order (P–delta) effects nor path dependency effects. Subsequently, the REMP is applied to various frames to illustrate the analysis procedures and to study the variation of lower bounds of collapse loads in the iterative process and collapse mechanisms, the latter by observing the hinge sequence. Further, a new strategy is proposed to apply the REMP including both constant and proportional loading on structural models. Following the descriptions and results of some numerical examples, this paper concludes primarily on satisfactory approximations of collapse loads and failure mechanisms calculated using the REMP. In earthquake engineering practice if the earthquake motions are simulated as equivalent static proportional loads, the REMP may be a useful and economical tool in the implementation of performance based design procedures in preliminary engineering, in verification processes, in structural optimization, and when facing complex geometric configurations. The REMP can be used to estimate approximations of both load redistribution in collapse conditions and failure modes when assuming different lateral load patterns along with gravity loads. It can be useful to determine optimum cross-section properties and the most convenient failure modes in new structures or weak links in existing structures.

2. Literature review

2.1. Introduction

A survey of the literature on applications of MVP shows that several inelastic parameters can be calculated by using repeated elastic finite element analysis with special variation of the element elastic moduli to simulate inelastic behavior in localized areas. Researchers in [3,5,6,8,13–15] studied MVP in finite element analyses for solids (plane stress, plane strain, axisymmetry), plates, shells, and beam elements, with emphasis on pressure vessel and piping systems. Although these researchers did not provide rigorous analytical support for most of those applications, numerical results confirmed their conclusions: results of MVP were compared with detailed inelastic analyses and, in a few cases, with experimental results. Moreover, for civil engineering applications, elastic methods using either reduced modulus concepts or reduced cross-section properties are described by Timoshenko [16], by Phillips [10], and by Mrazik et al. [9].

In local high stressed elements, the iterative process of MVP creates hypothetical paths (relaxation paths) in each stress–strain state. Mackenzie et al. [6], Marriott [8], and Seshadri [14] suggest that relaxation paths are insensitive to the nature of the material constitutive law and are characterized by the geometry of the structure when constrained by elastic elements. Thus, the relaxation path may be obtained using any convenient constitutive relation to reduce stiffness of local areas. MVP are organized into the following categories: (i) the REMP, proposed by Jones and Dhalla [3] and by Severud [15] and then extended by Marriott [8]; (ii) the GLOSS analysis and the R-node method, introduced by Seshadri [13,14]; and (iii) the ECM introduced by Mackenzie et al. [5] and studied recently by Ponter et al. [11,12].

2.2. Reduced elastic modulus procedure

The REMP, which is the original MVP, was proposed initially by Jones and Dhalla [3] to categorize stresses in piping systems. It has been used to estimate stress–strain states for highly stressed components in piping systems, thermal stress classification and the relationship to failure modes, inelastic strains, multiaxial relaxation, creep, fracture parameters, shape optimization, limit loads and shakedown loads. To evaluate limit loads, the REMP is used to create equilibrium states of stresses suitable to apply the lower bound theorem. At each iteration, an equilibrium solution is obtained and the stress field satisfies the lower bound theorem if the maximum calculated stress satisfies the yield condition; then, the applied load becomes a lower bound. To apply the REMP, an elastic analysis is first conducted with uniform moduli; the moduli are reduced in the elements in which the calculated stress exceeds the yield stress; the reduction is proportional to the ratio of the yield stress and the calculated stress. After completing a new analysis with the new moduli, the same strategy is repeated until either the maximum stress in the model is reduced to a value smaller than the yield stress or the convergence to some stress greater than the yield stress occurs. At each iteration, a lower bound of the limit load is calculated by scaling the solutions to satisfy the yield condition.

2.3. GLOSS method and R-node method

Similar to the REMP, Seshadri et al. [13] introduced GLOSS analysis which uses elastic analysis changing moduli in the high stressed elements to calculate inelastic strains and parameters related to inelastic deformations. Moreover, Seshadri et al. [14] proposed the R-node method to evaluate limit loads. In this procedure, the high stressed elements experience reduction in the moduli, while low stressed elements increase their moduli.