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Nonlinear dynamic behavior of steel framed roof structure with self-centering members under extreme transient wind load

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ABSTRACT

Collapse of roof could cause severe economic loss and poses safety risk to residents in the building. This paper presents a nonlinear dynamic analysis of steel framed roof structures with force limiting devices under combined static and transient wind loading. Two types of force limiting devices – one with self-centering behavior and the other exhibiting bilinear-like hysteresis are examined for roof collapse prevention. A nonlinear dynamic analysis that accounts for both material and geometrical nonlinearities was carried out for this simulation study. Two types of steel framed roof structures – a K-series steel joist and an arch truss are selected as the prototype roof frame in this study. It is found that installing force limiting devices at intentionally weakened zone of the prototype steel framed roof structures helps mitigating the displacement demand of the roof frame structure under transient up-lift wind pressure and thus reduce the dynamic collapse risk. Furthermore, the force limiting devices with self-centering behavior minimizes the residual deflection of the roof structures after the wind event.

1. Introduction

Steel structural framings is a popular structural form to cover the large roof space of gymnasiums, industrial facilities and transportation terminals, with potential use as shelter structures for a disastrous event such as hurricanes. However, under high winds, either part of the roof enclosure or the entire roof structure can be lifted off a building, particularly for low sloped roofs subject to wind-induced suction force. Collapse of roof could cause severe economic loss and poses safety risk to residents in the building.

Transient change in wind pressure may happen during a severe windstorm such as downburst and impose dynamic uplift load on low sloped roof structures. Such dynamic uplift load may cause failure of certain members in roof frames which may initiate the collapse of a steel framed roof structure as a result of load redistribution. The failure or rupture of members in a steel framed roof structure, may be dynamic in nature [31,14] and thus a nonlinear time history analysis is required to faithfully capture the dynamic collapse behavior of roof frames under transient wind loads. The collapse of a steel roof frame structure can be initiated by the buckling of a few members, as a result of load redistribution causing a subsequent progressive overstress condition in other members and thus its load carrying capacity is usually limited by the failure of first member or set of members to fail.

In an attempt to alter the brittle collapse behavior of steel roof frame structures under extreme wind loading, force limiting devices (FLD) can be used for robustness enhancement. These devices are fitted to critical compression members, and designed to provide a purely plasto-elastic behavior with a long plateau of member ductility (e.g., as exhibited in buckling-restrained braces). Since collapse is initiated by only a few critical members, the use of force limiting devices can be limited to a small selection of the most critical compressive chord or web diagonal members. The feasibility of using force limiting devices for controlling the behavior of space truss was validated in a research conducted by El-Sheikh [8]. The principle behind using these devices is to introduce artificial ductility in truss compression members, which would otherwise possess brittle post-buckling characteristics involving a loss of both stability and strength upon buckling. However, large residual deformations in conventional force limiting devices after strong loading events can make the structure appear unsafe to occupants, impair the structural response to a subsequent loading and significantly increase the cost of post-event repair or replacement.

Recognizing the importance of controlling the residual deformation, self-centering seismic resisting system has recently been attracting considerable attention from the community (e.g., [23,3,35]). A flag-shaped hysteresis loop is typical of such self-centering systems, which is able to reduce (or even eliminate) residual structural deformation. Dolce et al. [6] tested Nitinol-based devices with full re-centering and good energy dissipation capabilities. Zhu and Zhang [35] studied a special type of bracing member termed

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self-centering friction damping brace (SFDB) which exhibits a flag-shaped hysteresis loop and has a potential to be used for force limiting devices with self-centering behavior. In the SFDB, the self-centering ability is realized using super elastic SMA wires while its enhanced energy dissipation capacity is achieved through friction.

This paper presents the numerical study results of dynamic collapse risk mitigation of steel framed roof structures by installing force limiting devices under combined gravity load and transient wind loads. Both material and geometric nonlinearities are considered in the nonlinear dynamic collapse analysis. The formulations are 2-dimensional in this study. In the nonlinear analysis, dynamic effects associated with sudden loss of member capacity due to buckling and lateral inertial forces at the mid-length point of a buckling member are considered. Two numerical examples – one from a standard Steel Joist Institute (SJI) K series joist and the other on an arch tubular truss were used to demonstrate the effectiveness of the force limiting devices in mitigating the dynamic collapse risk of steel framed roof structures under transient wind load.

2. Nonlinear dynamic analysis procedure

To accurately simulate the dynamic collapse of steel roof framing structures subjected to combined gravity and transient wind load, non-linear time history analysis was performed in this study. The finite element model, that considers dynamic member buckling, yielding of tension members, and geometric nonlinearity due to large deflection of the roof structures undergoing collapse, is established using the OpenSees simulation platform [17].

A progressive collapse refers to a structural failure that is initiated by localized structural damage and subsequently develops, as a chain reaction, into a failure involving a major portion of the structural system [7]. Several mechanisms might contribute or lead to the progressive collapse of steel roof frame structures including: buckling of compression member, yielding of a tension member, facture of a tension member or connector, and nodal instability. The collapse of a steel frame structure can be initiated by the buckling of a few members [1], and its load carrying capacity is usually limited by the failure of first member or set of members to fail.

In this study, a 2-dimensional force-based element with corotational formulation and fiber discretization of the cross section was adopted for the simulation of buckling, post buckling, and hysteretic responses of members in steel roof frames. In this force-based corotational element, both material and geometric nonlinearities are considered.

The formulation of force-based elements is based on interpolation functions for the internal force variation [30]. Neuenhofer and Filippou [21] formulated a force-based element for geometric nonlinear analysis of plane frame structures, with linear constitutive relationship and small rotations. Following that, de Souza [26] extended the material nonlinear force-based element proposed by Neuenhofer and Filippou [20] to include geometric nonlinearity through deriving the transverse displacements from the curvatures using Lagrangian polynomial interpolation. The adopted kinematics is based on the assumption of moderately large deformations along the element; rigid body displacements and rotations can be arbitrarily large. However, at a price of further subdividing the structural member into smaller elements, large deformation problems can also be solved.

In the analysis of frame elements, the material nonlinearity is considered by integrating the material stress-strain relations defined for each fiber over the section area, which is commonly referred to as “fiber discretization”. Distributed plasticity is obtained by integration of the section force-deformation response over the member length in the corotating frame of reference. As shear effects are neglected, a uniaxial stress-strain relation is employed at the material point. The effect of spreading of plastic deformation along the member axis is thus considered in this study.

The following equation of motion is used for nonlinear time history analysis,

$$\mathbf{M}\ddot{\mathbf{U}}(t)+\mathbf{C}\dot{\mathbf{U}}(t)+\mathbf{R}(\mathbf{U}(t))=\mathbf{P}_f(t) \tag{1}$$

where the first term is the acceleration-dependent inertial force vector, $\mathbf{R}$ is the displacement-dependent restoring-force vector. $\mathbf{P}_f(t)$ is the external applied-force vector.

The standard approach for dynamic collapse analysis, as well as other nonlinear structural dynamic problems, is to time discretize the governing equations by Newmark time integration then solve them via the Newton-Raphson algorithm [28]. In this study, the Newmark constant average acceleration method ($\beta = 0.25$ and $\gamma = 0.50$) is employed. This requires that iteration must be performed at each time step in order to satisfy equilibrium. Also, the incremental stiffness matrix must be formed and triangularized at each iteration or at selective points in time.

3. Numerical analysis model

This section describes the components used in the numerical simulation of the dynamic collapse of steel roof frames under combined transient wind loading and gravity load. A finite element analysis software program –OpenSees [16] is used in this study.

3.1. Analytical model for dynamic member buckling

Modeling of the buckling behavior of steel bracing members has been examined by a number researchers (e.g., [11,33,12]. An initial imperfection has to be assigned to the axially loaded member to simulate its buckling behavior. However, few studies have considered the dynamic buckling effect of a compression member caused by the mid-point-inertia-mass (mid-mass)-induced lateral force at its mid-length [31].

The prototype member is a steel tube (O.D = 4.5 in (114.3 mm), I.D = 3.83 in (97.28 mm)) with a material yield strength of 30 ksi (206 MPa). The member length is set to be 80 in. (2.32 m). To capture the inertia effect on member dynamic buckling, a lumped mass which represents half the mass of the member is assigned to the middle-length point of the member following a procedure described by Tada and Suito [31]. A parametric study has been conducted and the results revealed that a finer meshed model has very little effect on the global collapse behavior of the roofs. Therefore, a single mass lumped at mid-length was used in all cases. The end conditions are specified as pin-roller supported, as shown in Fig. 1. Thus, the member was divided into two inelastic beam-column elements with an initial camber of 0.1% at the mid-node of the member in the finite element model, as shown in Fig. 1.

In this element, fiber discretization was used and the force components were obtained by integration over the cross-section. The tubular section of the member was discretized into two layers of fibers in the radial direction and 20 fibers in the circumferential

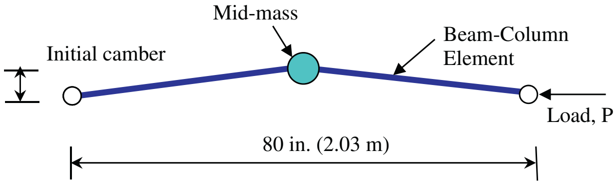

Fig. 1. Configuration of brace model considering mid-length mass.