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Dynamic behavior of upgraded rocking wall-moment frames using an extended coupled-two-beam model

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ABSTRACT

Rocking wall-moment frames (RWMFs), which perform well in controlling the soft-story mechanism, can achieve an enhanced performance by substituting their pinned base by a variable base rotational constraint provided by replaceable self-centering and energy dissipation devices. Rather than experiencing damage inside the moment frames, those upgraded RWMFs show a high potential towards seismic resilience by transferring damage to the replaceable base rotational constraint. The effect of this rotational constraint and the stiffness ratio between the moment frame and rocking wall on the dynamic behavior of upgraded RWMFs is investigated with the aid of an extended coupled-two-beam model proposed in this paper. In this model, the rocking wall and moment frame are represented by a linked flexural beam and a shear beam, respectively. The model replaces the fixed base of the flexural beam by a rotational spring to take the variable base rotational constraint into account. Closed-form solutions for modal displacement shapes, modal drifts, modal shear force and modal moment are derived. The model is verified with finite element analysis, and modal contributions to seismic response and drift concentration factor demand under earthquakes are investigated. It is found that within identified ranges of the rotational constraint and the stiffness ratio between the moment frame and rocking wall, a relatively good uniformity of story drift distribution is obtained and the higher modes effect caused by the full releasing of the rocking wall is mitigated. The model, the derived interstory drift spectra and drift concentration factor spectra can serve as useful tools for preliminary resilience oriented design purpose.

1. Introduction

Benefiting from the full releasing of base rotational constraint of rocking walls, rocking wall-moment frames (RWMFs) show an excellent performance in controlling drift distribution along their height [1,2]. A similar behavior is also observed in continuous gravity columns that can significantly decrease the possibility of serious drift concentration in steel concentrically braced frames [3]. Expanding the concept of the rocking wall to more concrete configurations, Qu et al. [4] proposed rocking cores to mitigate drift concentration in multi-story steel concentrically braced frames. Although the specific construction and implementation methods are different for the previous three cases, they all share a common mechanism, the use of the stiffness of a pinned continuous element over the height of structures, to avoid the occurrence of drift concentration at some local stories. This means that if only uniformity of drift distribution is expected with the pinned continuous element, the damage will still be redistributed inside the frame itself. The original intention of introducing rocking walls is to mitigate soft-story collapse mode under earthquakes in multi-story buildings. Thus, RWMFs are still designed to satisfy life safety requirements by dissipating seismic energy through inelastic deformation in structural members.

Rather than redistribute damage inside the frame itself, the RWMFs can be promoted to an upgraded version with high potential toward seismic resilience, according to which buildings should remain partially usable and quickly recover full function under earthquakes with a specified intensity. One effective strategy reported in literatures is to assign supplemental self-centering (prestressed tendons [5], a secondary elastic frame [6] etc.) and energy dissipation devices (self-centering energy dissipation braces [7], buckling restrained braces [8] etc.) by using the base moment-rotation response in the pinned continuous element, such as the rocking wall. The philosophy of this strategy is to concentrate damage on replaceable energy dissipation devices and to prevent the structural members from suffering damage. On one hand, these supplemental self-centering and energy dissipation devices provide additional resistance and protect the structural members from being damaged. On the other hand, they can be easily replaced so as to reduce the downtime of the structure as much as

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possible. Therefore, from the viewpoint of seismic resilience, the upgraded RWMFs can achieve much better performance than the conventional ones.

It is important to understand the dynamic characteristics and behavior of upgraded RWMFs before conducting an efficient design for them. Recent researches on RWMFs provide some references in this respect for the upgraded RWMFs. A distributed parameter model, which simulates the rocking wall and frame as a flexural beam and a shear beam, respectively, was developed by Pan et al. [9] to assess the strength demand of the rocking wall in RWMFs. This distributed parameter model, which is characterized by a dimensionless parameter, the stiffness ratio between the shear beam and the flexural beam, was statically analyzed to study the effect of rocking-wall stiffness on the drift concentration factor (DCF) demand. Directly adopting the assumption that the dynamic response of RWMFs is dominated by the first mode, Makris and Aghagholizadeh [10] idealized the RWMF as an elastic single-degree-of-freedom (SDOF) oscillator coupled with a rocking wall to investigate its dynamic response. The SDOF assumption was also adopted by Grigorian et al. [11], in conjunction with the assumption that the rocking core or rocking wall was rigid enough to impose uniform or near uniform drift along the height of the frame. However, despite the fact that the aforementioned studies provided some information on the behavior of upgraded RWMFs, some key issues are still not well understood. It was found that the releasing of base rotational restraint, whether caused by a rocking mechanism in the RWMFs or the forming of a plastic hinge at the base of shear walls, could be more influential for higher modes [12,13]. Therefore, the first key issue is that of the higher modes effect on dynamic response of upgraded RWMFs. The second key issue is to quantify the relationship between the DCF demand and the stiffness ratio between the rocking-wall and the frame in upgraded RWMFs, from the dynamical perspective. Finally, the third key issue is to study the effect of the supplemental rotational constraint at the base of the rocking wall provided by self-centering and energy dissipation devices and quantify the relationship between the DCF demand and the supplemental rotational constraint. It is obvious that the higher modes effect, the response distribution along the height of structures and the quantified relationship between these parameters are major concerns in these key issues.

Although finite element analysis (FEA) model can be used to conduct the elastic and elastoplastic dynamic analysis of upgraded RWMFs, it only provides information for a specified case with time-consuming analysis process. Even though they can be simplified as a multi-degree-of-freedom (MDOF) model, structural matrices (i.e., mass matrix, stiffness matrix etc.) needing cross sections of structural members are inevitably involved in the dynamic analysis. Compared with the previous two models, the distributed parameter model, which can be easily subjected to dimensionless parametric analysis, has been confirmed to be a good choice for solving problems associated with similar issues [14,15]. Hence, based on the widely used coupled-two-beam (CTB) model [16–21], an extended coupled-two-beam (ECTB) model is proposed in this paper. What the two models share in common is that they both consist of a shear beam and a flexural beam, which represent the frame and the rocking-wall, respectively. However, the ECTB model extends the CTB model by introducing a variable rotational constraint at the base of the flexural beam to represent the base rotational constraint provided by supplemental self-centering and energy dissipation devices added to the upgraded RWMFs.

The purpose of this paper is to investigate the dynamic response of the upgraded RWMFs with the proposed ECTB model. To facilitate parametric studies on this model, the stiffness ratio between the frame and the rocking wall, and the stiffness ratio between the rocking wall and its base rotational constraint are respectively represented by two dimensionless parameters α and Rf. Closed-form solutions for modal displacement shapes, modal drifts, modal shear force and modal moment are derived, and parametric studies on these modal response quantities are conducted to reveal the effect of the two dimensionless parameters α and Rf on the dynamical properties of the model. Then, the ECTB model is verified with the finite element analysis results using OpenSees software through comparisons of the modal displacement shapes and seismic responses [22]. Lastly, two applications of this model are demonstrated for the upgraded RWMFs. One has to do with the study of the effect of the two dimensionless parameters α and Rf on modal contributions to seismic responses, especially higher modes. The other application has to do with the establishment of a relationship between the interstory drift ratio demand and the DCF demand, and the two dimensionless parameters α and Rf, with the interstory drift spectra and the proposed DCF spectra.

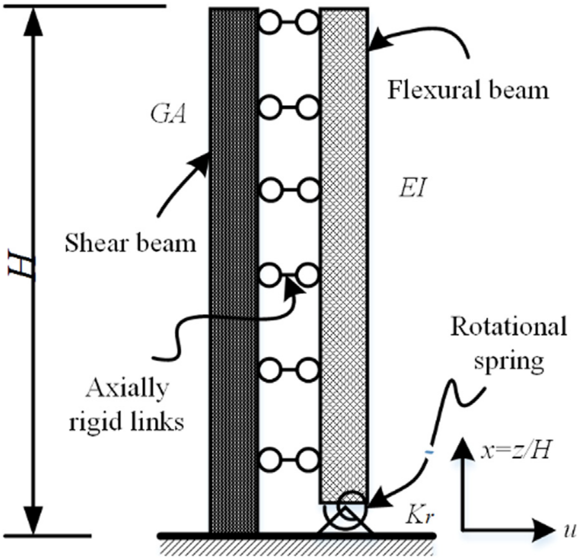

Fig. 1. ECTB model for upgraded RWMFs.

2. Dynamical properties of the upgraded RWMFs using the ECTB model

Based on a continuum approach, the ECTB model possesses unique advantages in characterizing response distribution along the height of structures, accounting for the effect of higher modes on seismic response and capturing key properties under the interaction of the rocking wall and the frame. Fig. 1 shows the ECTB model for the upgraded RWMFs. The shear beam and the flexural beam are in parallel connected with each other by axially rigid members that transmit horizontal forces. Thus, the two beams are constrained to have the same lateral deformation at all heights. In addition, the two beams are assumed to have uniform stiffness and mass along the height. To keep in line with the ECTB model, the upgraded RWMFs should comply with the following assumptions: (1) respond elastically when subjected to earthquakes; (2) should be symmetrically arranged and have story heights, cross-sections and modulus of elasticity constant over the height; (3) have floor systems infinitely rigid in their own plane; (4) have frames for low-rise or mid-rise buildings that produce only shear-type deformations and slender shear walls that generate only flexural-type deformations.

Even though the ECTB model shown in Fig. 1 has a variable amount of base rotational restraint at its boundary, it shares the same partial differential equation of motion as the continuum model used by Miranda and Akkar [23]. Thus, its motion under a horizontal acceleration at the base has the form

$$(\rho/EI)\partial^2u(x,t)/\partial t^2+(1/H^4)\partial^4u(x,t)/\partial x^4-(\alpha^2/H^4)\partial^2u(x,t)/\partial x^2 = -(\rho/EI)\ddot{u}_g(t) \quad (1)$$

where ρ represents the mass per unit length in the model, $u(x, t)$ denotes