Engineering Structures 73 (2014) 100–113

Contents lists available at ScienceDirect

Engineering Structures

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

Design of coupled wall structures as evolving structural systems

Abdelatee A. Eljadei [a,*], Kent A. Harries [b]

[a] Paul C. Rizzo Associates, Inc., Pittsburgh, PA, USA
[b] Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA, USA

ARTICLE INFO

Article history:
Received 17 July 2013
Revised 1 May 2014
Accepted 2 May 2014
Available online 24 May 2014

Keywords:
Coupled walls
Coupling beams
Evolving systems
Performance-based design
Degree of coupling
Seismic loads

ABSTRACT

Coupled wall (CW) structures are outstanding lateral load resisting systems that not only reduce the deformation demands on the building, but also distribute inelastic deformation both vertically and in plan, between the coupling beams and the wall piers. When subjected to large seismic loads, coupling beams may deteriorate relatively quickly exhibiting both strength and stiffness degradation. This results in a rapid evolution in the performance of the CW system from behaving as a coupled wall system to behaving as a system of linked wall piers (LWP). This evolution of behavior is the focus of this work which considers a prototype 12-storey reinforced concrete coupled core wall (CCW) building. Five prototype variations, having the same wall pier pairs but degrading degrees of coupling were designed to study the effects of decayed coupling action. Elastic analyses using the equivalent lateral force (ELF) procedure and the continuous medium method (CMM) were used to establish initial proportions for the CCW prototype, and to determine the design forces and moments. Nonlinear static and dynamic analyses were conducted to investigate the CCW structural behavior, adequacy of the design, and the effect of the evolution of the structural form from a CCW system to a collection of LWPs. As expected, the structures having weaker coupling beams exhibited yield at lower lateral loads. The accompanying reduction in coupling stiffness, however, mitigated this effect although the wall pier demand clearly rose with reduced coupling. In every case, however, the walls embodied sufficient overstrength to permit the overall structure to perform well. An additional aspect of this work is that the wall piers in the CCW were significantly different in terms of their dynamic and geometric properties: the moments of inertia of the two wall piers of the CCW differed by almost an order of magnitude. The different wall pier capacities affected performance and require bi-directional pushover analyses but did not result in a significant reduction in capacity as may be initially intuited.

1. Introduction

Controlling the lateral displacement of a structure subject to seismic loads is a predominant issue in the design of mid- to high-rise buildings. This lateral displacement is considered to be a primary indicator of the degree of damage imparted to the structure and can additionally lead to unintended structure–structure interaction (i.e., pounding) if not controlled. Performance criteria in the performance-based design (PBD) approach are usually displacement based. Therefore, one goal in design is to provide adequate stiffness to ensure that this displacement is within acceptable limits.

Coupled walls (CW) are a common form of shear wall structure in residential and multi-storey commercial buildings. A CW system resist lateral forces through a combination of flexural behavior of the wall piers and 'frame' action imparted by the coupling beams: an axial force couple is developed in the wall piers through the accumulation of shear in the coupling beams. The stiffness of the coupling beams governs the behavior of CW systems. The impact of the shear resistance of the beams is to make the CW system behave partly as a composite cantilever, bending about the centroidal axis of the wall group. The resulting stiffness of the coupled system is much greater than the summation of stiffnesses of the individual wall piers acting separately as uncoupled walls or in parallel as a collection of linked wall piers (LWP).

In a structural system, where lateral forces are resisted by a combination of systems, the more flexible component will exhibit lower ductility demand than the stiffer component of the structure. In the case of a coupled wall structure, the 'frame' action, that is: the axial forces in the walls resulting from the accumulated shear in the beams, is stiffer than the flexural response of the individual wall piers. As a result, the coupling beams exhibit greater ductility demands and damage than do the wall piers. As the

* Corresponding author. Tel.: +1 (412) 825 2202; fax: +1 (412) 856 9749.
E-mail address: Abdelatee.Eljadei@rizzoassoc.com (A.A. Eljadei).

http://dx.doi.org/10.1016/j.engstruct.2014.05.002
0141-0296/

damage progresses, it results in a structural system that may rapidly evolve from behaving as a coupled wall (CW) system to behaving as a collection of linked wall piers (LWP). Allowing the behavior of CW systems to evolve into that of a pair (or collection) of linked cantilever piers raises a number of concerns with regard to the dynamic behavior of such a system. Based on the expected evolution of performance, the linked wall pier system will be subject to large demands since the system is presumably behaving as a stiffer CW system at lower performance levels. In a sense, this evolving behavior may be represented as a progressive reduction in the degree of coupling (doc):

$$doc = \frac{CL_W}{CL_W + \sum R_{wall}} = \frac{CL_W}{OTM} \quad (1)$$

where CL_W = Frame action of coupling beams, ΣR_{wall} = Moment resisted by wall piers, OTM = overturning moment.

If one considers the effective lateral stiffness of a CW system as a function of the doc, the effect of reducing the doc from an initial value (perhaps on the order of 55%) to a very low value (say 10%) results in an increase in structural flexibility (and therefore demand on the wall piers) on the order of 45% [1].

Traditional strength-based design (SBD) of CWs [2] often results in coupling beam demands in excess of capacities permitted by the concrete design code [1,3]. Inherently large redundancy factors associated with CWs, and directional effects [4] also result in increased shear demand on coupling beams. Studies have clearly shown that current strength-based analysis and design procedures typically result in excessive coupling beam shear and inadequate ductility [5,1]. It is clear from this discussion that the design of coupling beam elements is critical to the structural performance of a CW system. In this work, a performance-based design (PBD) methodology was used to design the CW system. PBD generally allows controlled non-linearity in specified structural members as long as certain structural and element performance criteria are satisfied. Also, it allows the designer to select how the structure will behave and provides the framework for selecting performance objectives for the structure.

A rational approach to CW design, founded on a PBD approach has been proposed [6]. The proposed PBD approach recognizes the preferred yielding mechanism of CWs [7] and takes advantage of the available ductility of the coupling beams. Fig. 1a shows an idealized response of a CW designed using a PBD approach. In the case shown, the coupling beams were permitted to yield at a base shear (V_B) lower than the code-prescribed design base shear (V_C at life safety (LS) performance objective) and the wall piers yielded at $V_W \approx V_C$. V_D is the base shear corresponding to the CW attaining its code-prescribed drift limit (typically 2%). Other performance spectra are possible such as allowing inelasticity in the wall piers at design base shear levels ($V_W < V_C$).

In the present study, it is conceived that different behavior may be permitted at different performance levels. For example, a CW may be designed to behave as a CW system at the life safety (LS) performance level but as a collection of linked wall piers at the collapse prevention (CP) level (essentially, having exhausted the capacity of the beams) as shown in Fig. 1b. In Fig. 1, the fundamental structure considered was represented by its structural period: T_{CW} for the CW system (Fig. 1a) and T_{CW} evolving into T_{LWP} where only the wall piers provide lateral force resistance following designed-for exhaustion of the coupling beam capacity (Fig. 1b).

2. Objectives of present study

The objective of this study is to introduce and demonstrate a performance objective based on accepting and even leveraging the behavior of dual or evolving structural systems. In this approach, the performance domain was defined as the structural form of the lateral force resisting system (LFRS) itself: the LFRS of the structure was permitted (indeed, encouraged) to evolve from one form to another based on increasing demand during a seismic event. This rapid evolution may then be optimized to affect both rational performance criteria at various demand levels and economy in design. The example considered was the evolution of coupled core wall (CCW) systems to systems of linked wall piers (LWP) at increasing lateral load demands, shown schematically in Fig. 2.

The concept is envisioned for a typical dual system as follows: The structure performs as a dual structure (in this case, as a coupled wall) at a particular (design) performance level. At a performance level having a greater demand, the capacity of one of the components of the dual system (coupling beams) is permitted to be exhausted as the structure essentially becomes a single LFRS structure (a collection of linked wall piers, in this case). Such an approach will result in a more rational performance for the structure and a more economical structural design particularly in cases where the components of the dual system have significantly disparate stiffness and thus proportional demands as is the case in CW.

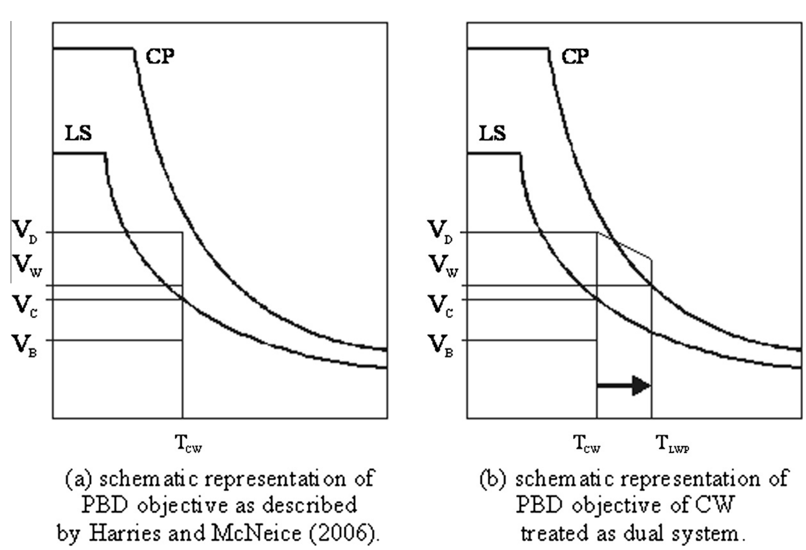

Fig. 1. Idealized spectral capacity behavior of a CW.