Numerical Evaluation of Plastic Region Propagation in Coupled Wall Systems

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SUMMARY
Coupling walls, where coupling beams spring between two RC walls, is a common construction method that aims to benefit from the energy dissipation of the beams while meeting the architectural needs. The optimization of the coupling ratio of these beams is needed in the design procedure since these beams simply allow the designer to control the basic design targets such as the target displacement, ductility and hysteretic damping.

The coupling ratio, being the most important design parameters in the design procedure of the coupled RC walls, is generally chosen at the beginning by the design engineer. The rest of the design follows this very initial assumption. This paper focuses on the variation of the coupling ratio and its comparison with the initially assumed one. A 8-story case study example is chosen to underline this behaviour. The case study structure is designed by using a displacement-based design method, and the initially assumed coupling ratio is checked in every step of the analysis. It is found that the coupling ratio is very high at the beginning where the displacement demand is small, and it goes below the initially assumed level before the target displacement is reached.

Keywords: Coupled Wall, Displacement-Based Design, MVLEM, Coupling Ratio, Flexure-Shear Envelope

1. INTRODUCTION

Parallel to the fast urbanization, a rapid increase in the construction of tall structures has taken place. RC walls are common lateral load bearing members in reinforced concrete multi-storey buildings since they are generally preferred conventionally to resist seismic demands. Coupled structural walls form an efficient structural mechanism for resisting seismic actions in high-rise structures meeting the architectural requirements at the same time. By connecting the considerable lateral stiffness of structural walls with properly proportioned coupling beams that can accommodate the most of the energy-dissipative mechanism during the response to earthquake motions, an exceptional behaviour of structural system can be achieved. Since plastic hinges are intended to form not only at the base of the walls but also at both ends of coupling beams, energy dissipation is distributed over a more extensive region of the structure with the result having higher damping than is the case with cantilever walls.

While coupling action between the walls separated by openings becomes important, the selection of analysis method to be used for designing of coupled wall systems is also crucial importance. Since the progression of plastic behaviour on coupling beams in tall buildings does not occur simultaneously along elevation, the coupling ratio of the coupled wall system cannot be expected as constant during the whole process of ground motion.

For a two shear wall system, the coupled wall is defined in Eqn. 1.1. below:

$$CR = \frac{L\Sigma V_{beam}}{OTM} \tag{1.1}$$

Where ΣV_{beam} is the cumulative result of coupling beam shears acting at the edge of one wall pier; L is the distance between centroids of the wall piers. CR=0 means that coupling beams does not contribute on end moments; on the other hand, 100% coupling ratio is the theoretical case where two wall piers effectively behave as a single pier. (El-Tawil et al, 2010).

2. DIRECT DISPLACEMENT-BASED DESIGN OF RC COUPLED WALLS

The design procedure known as Direct Displacement-Based Design (DDBD) has been studied and developed over the past fifteen years with the aim of mitigating the inadequacies in current force-based design (Priestley et al, 2007). The main phenomena behind the approach is to design a structure which would accomplish a defined performance limit state under a given given seismic intensity. The design procedure evaluates the capacities required at designated plastic regions to achieve the design aims in terms of displacement objectives.

The design method assumes a single-degree-of-freedom representation and it is applicable to all structural types, including coupled structural walls. The bi-linear behavior of the lateral force-displacement response of the single-degree-of-freedom is shown in Fig. 2.1. An initial elastic stiffness K_i is followed by a post yield stiffness of rK_i. While the force-based seismic design characterizes a structure in terms of elastic, pre-yield, properties, DDBD method evaluate the structure by secant stiffness K_e at maximum displacement Δ_d.

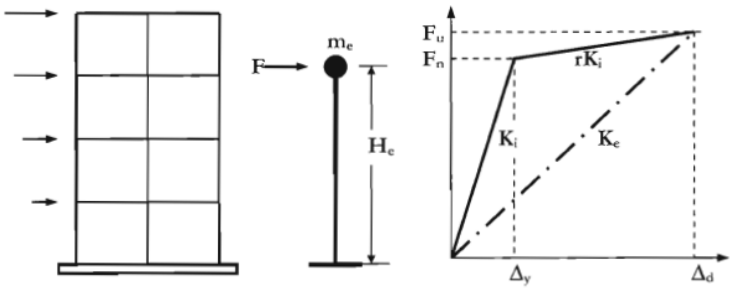


Figure 2.1. DDBD Single-Degree-of-Freedom representation (Priestley et al., 2007)

With the design displacement at maximum response determined, the effective period T_e at maximum displacement response, measured at at the effective height H_e can be determined from a set of displacement spectra for different levels of damping. The effective stiffness K_e of the equivalent single-degree-of-freedom system at maximum displacement can be found by inverting the normal equation for the period of a single-degree-of-freedom oscillator, given by Eqn. 2.1. to provide

$$K_e = 4\pi^2 m_e / T_e^2 \quad (2.1)$$

where m_e is the effective mass of the structure participating in the fundamental mode of vibration. From Fig. 2.1., the design lateral force, which is also the design base shear force, can be calculated from Eqn. 2.2.

$$F = V_{base} = K_e \Delta_d \quad (2.2)$$

Formerly, the value of coupling ratio defined in Eqn. 1.1. has been evaluated by using initial stiffness force-based design based on elastic analysis. On the other hand, further studies has shown that elastic analysis is not a logical procedure for determining the distribution of forces in coupled walls and coupling beams (Paulay, 2002). Coupling beams will yield at a ratio of a lateral load at which the coupled walls yield. This ratio between walls and beams normally be in the range 25% to 75%.

3. PROPOSED NUMERICAL MACRO MODEL FOR COUPLED WALLS

3.1. Multiple Vertical Line Element Model (MVLEM)

Modelling of the inelastic response of RC wall systems can be performed by using either micro models based on a comprehensive interpretation of the local response, or by using phenomenological macro models which take into account overall behaviour within acceptable accuracy. Although micro models can provide a sophisticated definition of the local response, their practicality, and reliability are questionable due to complexities involved in developing the model and interpreting the results. Macro models, on the other hand, are practical and efficient, although their application is restricted based on the simplifying assumptions upon which the model is based.

Usage of column-beam line element at the wall centroid axis is a well-known modelling approach. In this case, an equivalent column is is used to model the properties of the wall, and beams with high stiffness are bound to the column at each floor level. The rotations of a beam-column element always develop about the centroid axis of the element; therefore, neutral axis along wall cross-section during lateral loading and unloading is not taken into account. As a result, over-turning of the wall and interaction with any connecting elements, both in the plane of the wall and out-of-plane of the wall, cannot be adequately considered.

As a result of extensive studies, the multiple-vertical-line element model (MVLEM) proposed by Vulcano et al. (1988) has been shown to successfully balance the simplicity of a macroscopic model and the refinements of a microscopic model. The MVLEM captures essential response characteristics (e.g., shifting of neutral axis, and the effect of a fluctuating axial force on strength and stiffness), which are commonly ignored in simple models, and offers the flexibility to incorporate refined material constitutive models and important response features (e.g., confinement, progressive gap closure and non-linear shear behaviour).

The model in Fig. 3.1. is an implementation of the generic two-dimensional MVLEM wall element. The flexural response is simulated by a series of uniaxial elements connected to rigid beams at the top and bottom floor levels. The two external fibres (k_1 and k_n) represent the axial stiffness of the boundary columns, while the interior elements represent the axial and flexural stiffness of the central panel.

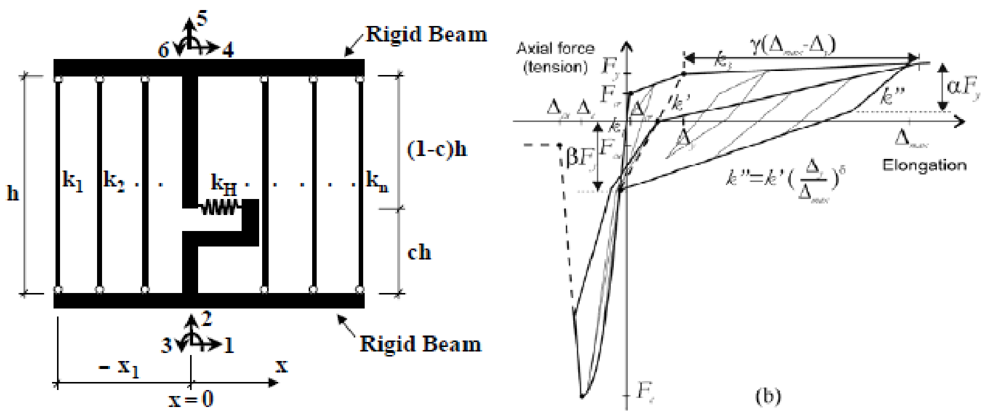


Figure 3.1. Multiple Vertical Line Element Model (MVLEM) (Orakcal et al., 2006)

3.2. Flexural Strength – Shear Strength Envelope in Coupling Beams

Together with the idealized flexural response, the shear model was used to categorize the three possible failure modes of coupling beams under lateral loads. They are shown in Fig. 3.2.

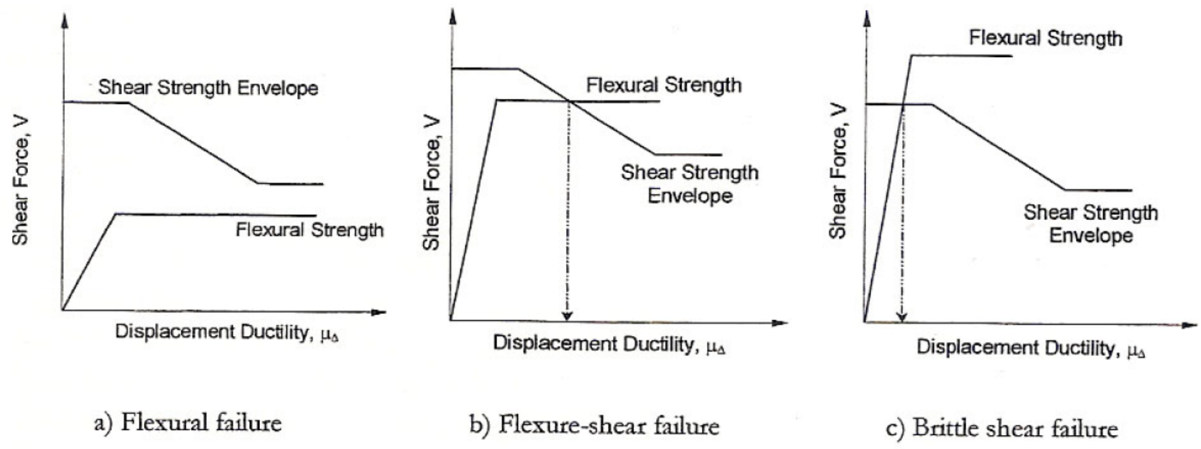


Figure 3.2. Classification of reinforced concrete coupling beam failure modes (Miranda et al., 2005)

Flexure failure takes place if the shear force corresponding to the nominal flexural strength is less than the shear capacity for any value of ductility. A typical flexural failure situation is shown in Fig. 3.2a. A flexure-shear failure occurs when the coupling beam reaches its nominal flexural capacity first, but as ductility increases the corresponding shear force exceeds the shear strength envelope. Shear failure is triggered at the point where the shear resistance goes below the flexural resistance. This situation is presented graphically in Fig. 3.2b. Finally, Fig. 3.2c. shows a brittle shear failure, which occurs when he shear capacity of the column is reached prior to the development of the flexural strength.

4. NUMERICAL ANALYSIS - CASE STUDY

The examined coupled wall system is selected as a case study that is designed with Direct Displacement Based Design (DDBD) approach. The DDBD procedure suggests assuming a coupling ratio a priori as the first step of the design procedure. The actual coupling ratio of the wall system has been investigated and compared with the initially assumed coupling ratio. The non-linear behaviour of the system is then examined by a simple pushover analysis with uniform and triangular loading patterns.

The sample coupled wall system consists of two identical 8 storey 4.00m x 0.30m walls connected with 2.00m long and 1.00m deep beams (aspect ratio = 2) at each floor level. 3D representation of the model is shown in Fig 4.1.

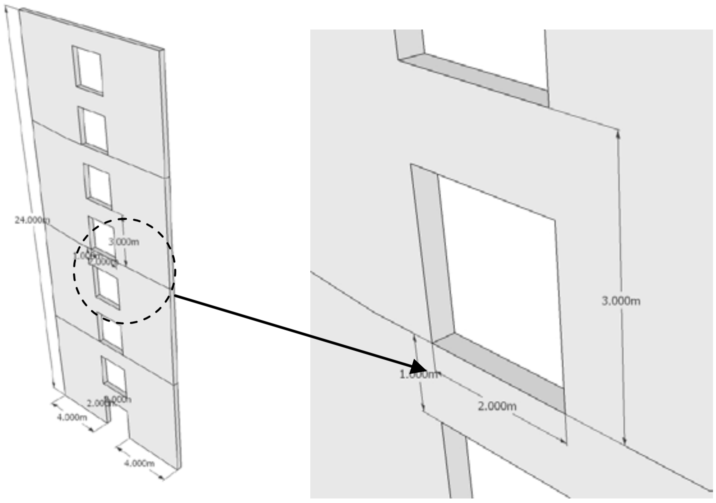


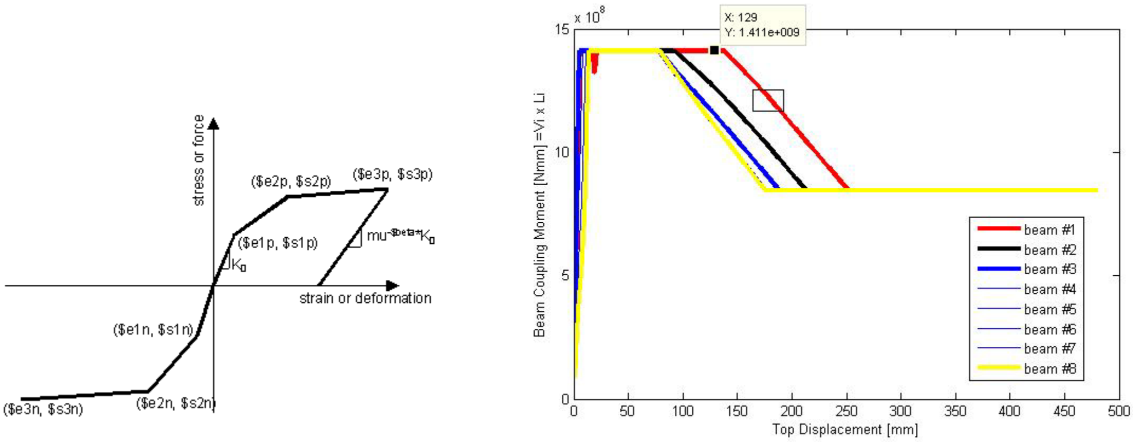
Figure 4.1. Case study model

Direct Displacement-Based Design procedure starting with a coupling ratio assumption of 40% results with beam design shear strength of 235kN. The nonlinear shear-deformation behaviour is modelled in OpenSees software (OpenSees, 2012) by using hysteretic model. Default properties of hysteretic force-deformation model is summarised in Fig. 4.2a.

It should be noted that, for the sake of simplification and abiding by the modern design concepts, the shear failure is omitted in the behaviour of the RC walls used in the case study. This is an issue that requires more work since coupling flexural and shear behaviours in RC walls is an open research topic that attracts much experimental and analytical work.

In order to adopt shear strength envelope given in Fig. 3.2, pinching effect is disabled from the default hysteretic back-bone curve. Additionally, post-yielding stiffness represents 40% of strength degradation. Resultant coupling moments (Vi x Li) for each individual story beam is summarized in Fig. 4.2b. It is observed that coupling beams located on lower stories have strength degradation later than the ones on upper floors.

Structural wall system coupling ratio analysis result is plotted on Fig. 4.3. The graph shows that actual coupling ratio starts with approximately 70% under elastic behaviour region. Then, it rapidly decreases down to 40% (DDBD assumption) at 100mm displacement. Actual coupling is 25% lower than the assumed DDBD coupling ratio under design displacement value of 296mm.



(a) **(b)**

Figure 4.2. The Hysteretic Model in OpenSees (left) and the beam coupling moment distribution with triangular load pattern (right)

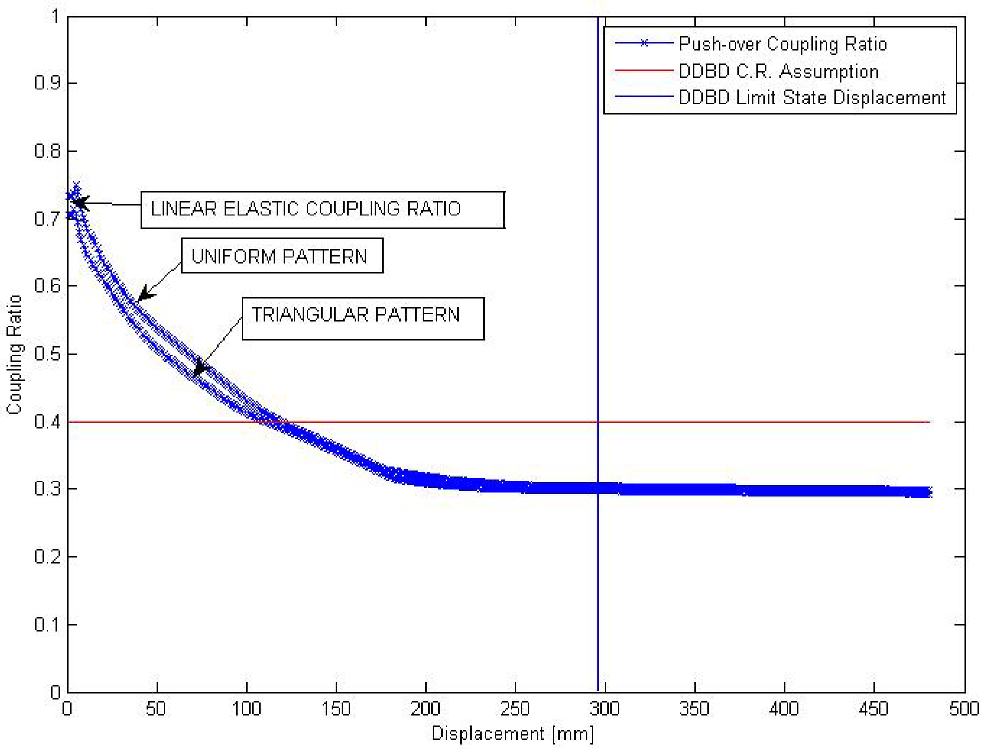


Figure 4.3. Coupling ratio vs top displacement

The plot in Figure 4.3 suggests that the coupling ratio of the beams, their contribution in other words, is much higher than the assumed initial design ratio, which was 40%. The increasing displacement demand on the structures, thus on these beams, lead to a drastic drop in the coupling ratio of these beams. For the given example, the coupling ratio, which is the most basic design parameter and assumption, drops below the initially assumed value before the design displacement is reached.

The findings in Figure 4.3 exhibit a variable behaviour of the beam-coupling ratio over the increasing deformations, something that has to be considered in design maybe by implementing different coupling ratios in different limit states. This issue requires further research.

5. CONCLUSIONS

Reinforced concrete coupled wall systems are frequently used in medium and high-rise building construction. The coupling action is beneficial, because it reduces the moments to be resisted by individual walls. Secondly, the plastic deformation (energy dissipation) is extended along the height of the wall rather than being only at the base of cantilever walls. The selection of analysis method to be used for designing of coupled wall systems is very important. Since the progression of plastic behaviour on coupling beams in tall buildings does not occur simultaneously along elevation, the coupling ratio of the coupled wall system cannot be expected as constant during the whole process of ground motion.

In this research study, a 8-story coupled wall system which is is designed with Direct Displacement Based Design (DDBD) approach is used as case study..A desired coupling ratio in DDBD procedure is assumed initially as the first step of the design. In this study, on the other hand, the actual coupling ratio of the wall system has been investigated and compared with the initially assumed coupling ratio. The non-linear behaviour of the system is then examined by a simple pushover analysis with uniform and triangular loading patterns. The conclusions obtained with the evaluations of the numerical solutions are summarized below:

1. Coupling ratio alteration is not significantly affected by the type of the lateral load pattern (triangular or uniform) for coupled wall systems under 8 storeys.
2. Initial coupling ratio (before coupling beams undergo plastic) is over two times than the coupling ratio value at design displacement. Therefore, analysing coupled wall systems under linear-elastic procedures would give unrealistic results.
3. The actual coupling ratio at design displacement is 25% lower than the DDBD-assumed coupling ratio value for the case study examined herein. The number of samples must be increased in order to further validate this finding.
4. The coupling beams at higher stories experience strength degradation initially. The coupling beams at first floors reach strength degradation significantly later than all other beams.
5. The effect of the coupling ratio going below the initially assumed value must be further investigated in terms of its effects on the validity of the design.

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