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PARAMETRIC STUDY OF COUPLED NON-LINEAR SHEAR WALLS ON FLEXIBLE BASES

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SUMMARY

The effect of flexible foundations under coupled shear walls subjected to static lateral loading is examined. The analysis is based on the continuum method with the assumption that coupling beams yield while the walls and supporting soil remain elastic. Supporting soil flexibility is represented by effective base stiffnesses K_θ and K_v varied in parametric fashion over a wide range. Results are presented for top displacement, distribution of coupling shear in the connecting beams, axial force and bending moment in the walls as well as ductility demand for the beams.

INTRODUCTION

Coupled shear walls are frequently employed in buildings to resist seismic forces since it is known that proper detailing can ensure adequate ductility. When such systems are founded on rock or supported by deliberately strong foundations, the common design practice is to assume fully fixed or rigid base conditions for the walls. However, in certain situations (i.e. when the walls are supported on footings resting on flexible soil such as dense sand and gravel) it may not be reasonable to ignore the flexibility existing at the wall bases. While studies exist (Ref. 1, 2) for coupled shear walls resting on flexible foundations assuming purely elastic behaviour in both the structure and the supporting soil, corresponding research concerning non-linear behaviour has not been reported.

Thus this paper presents the results of a parametric study of the importance of supporting soil base flexibility on the lateral load resistance of non-linear shear walls. Results are presented for a typical 20-story coupled shear wall structure with effective elastic rotational and vertical base stiffnesses K_θ and K_v varied independently from fully fixed to very soft base conditions.

METHOD OF ANALYSIS

Fig. 1 shows the geometry and loading of the coupled walls resting on flexible bases. The latter are represented by rotational and vertical stiffnesses $K_{\theta i}$, K_{vi} ($i = 1, 2$) under the walls. For increasing lateral load W, it is assumed that plastic hinges develop in the coupling beams, with the walls and supporting soil remaining elastic. Response is obtained employing the well-known continuum method wherein the coupling beams are replaced by a continuous connecting lamina introduced to transfer vertical coupling shear q over the height of the structure. The formulation is similar to that employed by Glück (Ref. 3) for fixed bases, but modified to include the effect of flexible foundations (Ref. 4). Foundation flexibility is represented in the formulation by effective rotational and vertical stiffnesses for the pair of coupled walls defined, respectively, by: $K_\theta = K_{\theta 1} + K_{\theta 2}$; and $K_v = K_{v1}K_{v2}/(K_{v1} + K_{v2})$.

Depending on the load level and also on the magnitudes of the base flexibilities, various states of connecting beam plastification as defined by the distribution of coupling shear q over the height of the structure may arise. These comprise the following: (1) State I - purely elastic; (2) State II - upper and lower elastic with a middle plastic zone; (3) State III - upper elastic and lower plastic zones; and (4) State IV - upper plastic and lower elastic zones.

OUTLINE OF PARAMETRIC INVESTIGATION

The prototype structure selected for study consists of 20-story coupled shear walls of T-shape cross-section (Ref. 5), with dimensions and section properties listed in Table 1. Base stiffnesses were varied in parametric fashion over a broad range encompassing the extreme cases of very flexible to fully rigid. For the present structure this involved effective rotational stiffness $1 \times 10^4 \leqslant K_\theta \leqslant 1 \times 10^9$ kN.m/rad and vertical effective stiffness $8.75 \times 10^4 \leqslant K_v \leqslant 1.75 \times 10^8$ kN/m. These values are in general agreement with those reported by Tso and Chan (Ref. 2) in their study of elastic walls on flexible foundations.

With the exception when behaviour is examined for increasing load, the parametric results are based on a standard load level given by W = 4300 kN. This load corresponds to the theoretical ultimate load for the prototype structure with pinned bases (K_v = rigid; $K_\theta = 0$) and thus allows the parametric variation of K_v and K_θ over the full range of values noted above. The theoretical ultimate load itself is defined to occur upon complete plastification of the coupling lamina over the height of the structure. In terms of ductility demand μ in the coupling beams, defined by $\mu = \theta_b/\theta_y$ where θ_b is the maximum beam rotation and θ_y is the beam yield rotation, W = 4300 kN corresponds to a ductility demand $\mu = 2$ for the condition of rigid bases. For typical footings resting on dense sand and gravel, on the other hand, the corresponding ductility demand is $\mu = 4$ ($K_\theta = 3.5 \times 10^6$ kN.m/rad, $K_v = 5 \times 10^5$ kN/m).

RESULTS AND DISCUSSION

Examined below are the parametric results reported in terms of the distribution of coupling shear q, bending moment and axial force at the base of the walls, ductility demand in the coupling beams and top displacement as functions of effective base stiffnesses K_θ and K_v.

Distribution of coupling shear Typical distributions of coupling shear q to be expected for different base flexibilities with W = 4300 kN are presented in Fig. 2, where q is normalized with respect to the ultimate shear capacity q_u of the connecting lamina. The relative magnitudes of effective base stiffnesses K_v and K_θ give rise to any of the four forms of the laminar shear distribution shown. It should be noted that, for flexible bases, the coupling shear has a finite value at the base (Figs. 2(b) - 2(d)), whereas for rigid bases the coupling shear vanishes at this level (Fig. 2(a)). For a given pair of coupled walls, the ratio K_θ/K_v determines whether the base coupling shear q_o is positive, negative or zero, while the magnitude of q_o depends on the actual values of K_θ and K_v. Whereas the classic non-linear shear distribution of Fig. 2(a) is generally attributed to a rigid base, $q_o = 0$ may also occur for certain other combinations of K_v and

K_θ. Apart from the evident importance of base flexibility in predicting the behaviour of coupling beams near the base of the structure, the most interesting case is that of Fig. 2(d) where low magnitude of K_v (or equivalently, high K_θ/K_v ratio) results in the foregoing reversal in the sign of q_o.

It should also be noted that further increase in load W will eventually cause the plastic zone of Fig. 2(a) to extend to the top of the structure, resulting in the aforementioned State IV plastification of the coupling beams at ultimate load. On the other hand, similar load increase for the cases of flexible bases generally results in extension of the plastic zone to the base first, thus producing State III plastification at large non-linear load.

Size of plastic zone The theoretical effect of base flexibility on the non-linear response of coupled shear walls can best be determined by studying its influence on the size of the plastic zone. In general, the size of the plastic zone is sensitive to both K_θ and K_v. Reducing the rotational base stiffness K_θ (for constant W) results in an increase in the plastic zone, whereas reducing the vertical base stiffness K_v results in a decreased plastic zone. Releasing further the rotational stiffness of a "three-zone" State II case of beam plastification will produce the "two-zone" condition of State III.

Load-displacement relationship The load-displacement curves for different base stiffnesses are shown in Fig. 3 plotted up to the ultimate state where plastification of all coupling beams has occurred. It can be seen from Fig. 3(a) that varying the vertical stiffness K_v from rigid to very flexible base conditions results in a 10 per cent increase in ultimate load, whereas varying the rotational stiffness K_θ from rigid to the pinned condition results in a 33 per cent decrease in ultimate load, as shown in Fig. 3(b). This indicates particular sensitivity to rotational base stiffness of the ultimate load carrying capacity of the structure. On the other hand, the top deflection at ultimate load appears to be sensitive to both vertical and rotational base stiffnesses, showing maximum increases over rigid bases of 87 and 61 per cent, respectively.

Coupling beam ductility demand The need to provide adequate ductility capacity in the coupling beams plays a key role in the design of coupled shear walls since, in practice, failure is often associated with excessive beam ductility demand. Fig. 4 shows ductility demand as a function of K_θ and K_v. Plotted separately is the maximum ductility demand μ over the entire height (Fig. 4(a)) and the ductility demand μ_o incurred at the base itself (Fig. 4(b)). The dashed portions of the curves in Fig. 4(b) indicate anticipated, rather than actual, ductility demand at the base since the present formulation assumes elastic behaviour at the base of a "three-zone" state of coupling beam plastification (State II and Fig. 2(d)).

Fig. 4(a) shows that the maximum beam ductility demand in the structure above the base exhibits strong sensitivity to both rotational and vertical base stiffnesses over the range $1 \times 10^5 < K_\theta < 5 \times 10^6$ kN.m/rad, and is relatively insensitive to both K_θ and K_v outside this range. However, ductility demand μ_o at the base remains sensitive to effective vertical base stiffness K_v even at large magnitudes of K_θ, as seen in Fig. 4(b). Another important observation is that μ_o exhibits the expected reversal in sign for low values of K_v coupled with large magnitudes of K_θ; hence vertical settlement of the foundation dominates the response of the connecting lamina at the base of the structure. Indeed, for large K_θ and a vertically non-rigid foundation, the peak ductility demand will occur in the lowermost coupling beam.

Assuming a design ductility capacity given by $\mu = 4$, the range (-10 to +28) encountered in Fig. 4 confirms the known importance of coupling beam ductility in the design of coupled shear walls; at the same time, it demonstrates the sensitivity of this design parameter to flexibility of the supporting foundation.

Forces in walls Axial force Q_o and bending moments $M_{o,i}$ ($i = 1, 2$) incurred at the bases of the walls at constant W = 4300 kN are shown in Figs. 5 and 6 as functions of K_θ and K_v. It is seen that large values of K_θ coupled with reduced values of K_v result in decreased axial coupling and a corresponding increase in resistance through bending of the walls and, conversely, low rotational base stiffness increases the demand for resistance through axial coupling. However in general, compared to rigid bases, flexible foundations may result in either larger or smaller forces at the bases of the walls, depending on the magnitudes of the effective base stiffnesses. Compared to fixed bases, K_θ and K_v for typical footings on dense sand and gravel result in increased base axial force Q_o of 6.5 percent and decreased base bending moment M_o of 23 percent ($M_o = M_{o,1} + M_{o,2}$).

Lateral stiffness Treating top displacement as the measure of overall lateral stiffness of the coupled walls, Fig. 7 shows the influence of base flexibility on this important property of the structure. In general, it is observed that top deflection is more dependent on vertical stiffness K_v than on rotational stiffness K_θ, becoming particularly sensitive to K_v when K_θ is relatively small. With low K_v, on the other hand, rotational stiffness K_θ becomes equally important. For large K_θ top displacement, and hence lateral stiffness, is insensitive to both K_θ and K_v. For the practical situation of intermediate base flexibility, the trend is for displacement and lateral stiffness to be more sensitive to vertical stiffness K_v than to rotational stiffness K_θ.

CONCLUSIONS

This study has examined the importance of base flexibility on the non-linear behaviour of coupled shear walls subjected to static lateral loading. From the parametric results, presented as functions of effective base rotational and vertical stiffnesses, the following conclusions affecting the design of coupled shear walls are noted.

1) Vertical flexibility as expressed by varying magnitude of K_v affects primarily the lateral stiffness with marginal effect on ultimate load of the structure, whereas K_θ influences strongly the ultimate load at which plastification of the coupling beams over the height of the structure occurs.
2) Whereas both K_θ and K_v affect the coupling beam ductility demand, low K_θ or low K_v coupled with large K_θ results in maximum ductility demand occurring in the lowermost coupling beam, i.e. at the base.
3) Axial force and bending moment at the base of the walls are sensitive to both K_θ and K_v; compared to fixed bases, flexible foundations result in wall base forces that are either larger or smaller as determined by the magnitudes of K_θ and K_v.
4) Data concerning the distribution of internal stresses (not presented herein), such as wall axial force and bending moment as well as coupling beam shear and ductility demand, indicate that while sensitive to base flexibility, the influence is limited to the lower portion of the structure except for load approaching the ultimate state.

In the present study, the effective vertical and rotational base stiffnesses were varied independently. In practice, however, K_θ and K_v are coupled, their ratio depending on both the supporting soil conditions as well as the type and size of the foundation itself. A more precise assessment of the effect of flexible foundations should incorporate these factors simultaneously. This is the subject of a current investigation.

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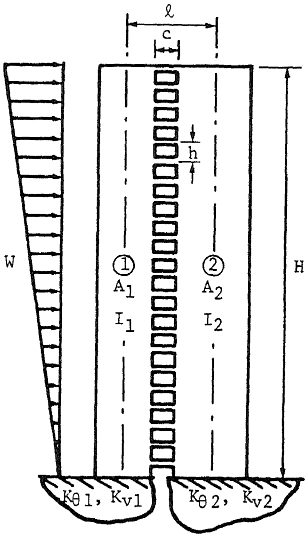

Fig. 1 Coupled shear walls on flexible bases

Table 1 Effective properties of prototype structure

Property	Value
Height, H (m)	53.4
Width of walls, d_1=d_2 (m)	3.66
Story height, h (m)	2.67
Beam span, c (m)	1.83
Wall thickness, t (mm)	356
Wall flange width, b (m)	2.14
Centroidal distance, ℓ (m)	6.56
Wall areas, A_1, A_2, (m^2)	1.35, 1.94
Wall moments of inertia, I_1, I_2 (m^4)	1.31, 2.62
Beam moment of inertia, I_b (m^4)	0.652×10^{-2}
Lamina shear capacity, q_u (kN/m)	438

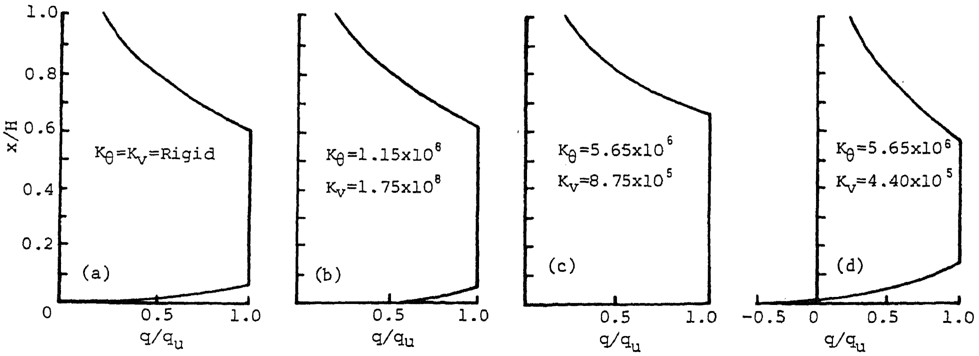

Fig. 2 Distribution of coupling shear q for different base stiffnesses: (a) rigid; (b) K_θ/K_v = 0.66; (c) K_θ/K_v = 6.5; (d) K_θ/K_v = 12.8 (K_θ, K_v in units kN, m, rad)

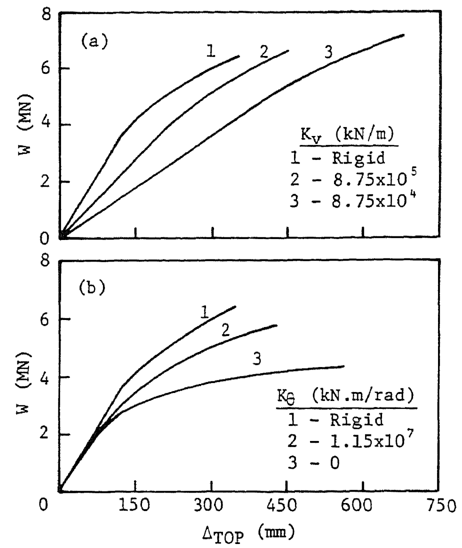

Fig. 3 Load-displacement behaviour as function of base stiffnesses: (a) K_θ = rigid; (b) K_v = rigid

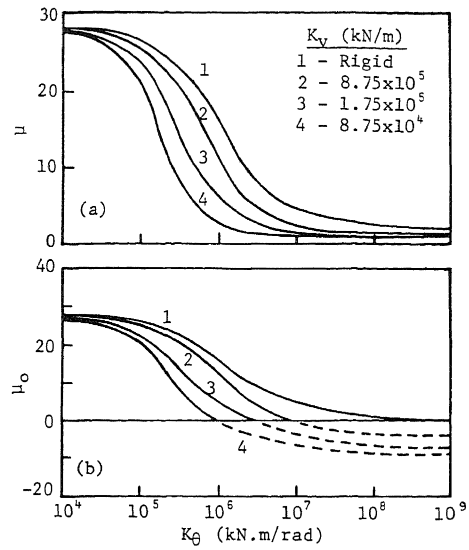

Fig. 4 Beam ductility demand as function of base stiffnesses: (a) entire height; (b) at base

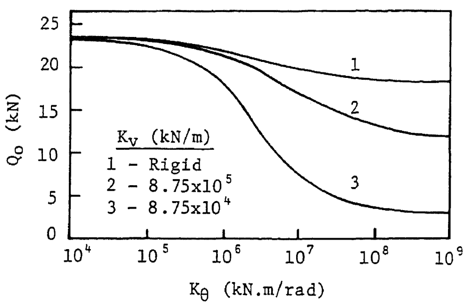

Fig. 5 Axial force in walls at base as function of base stiffnesses

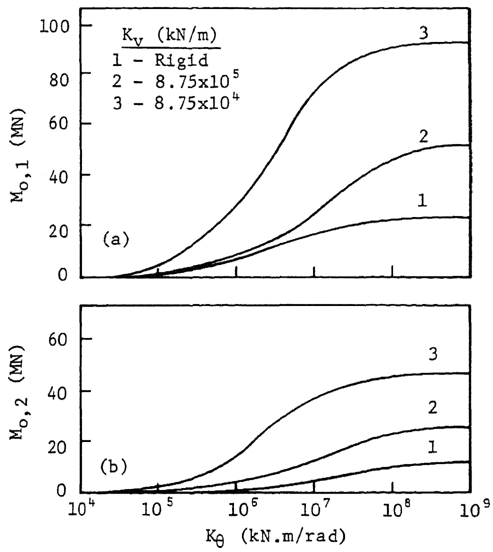

Fig. 6 Wall bending moments at base as functions of base stiffnesses: (a) wall 1; (b) wall 2

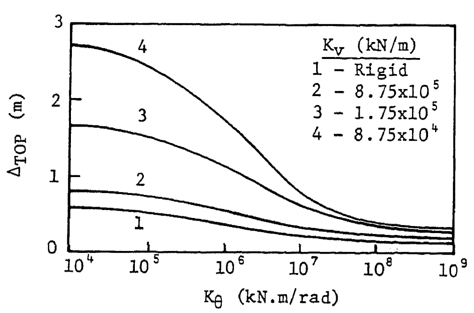

Fig. 7 Top displacement as function of base stiffnesses