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Elastic Response of Prefabricated Shear Wall

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Prefabricated shear (PS) walls may be analyzed by the finite element method, wherein the precast wall panels are represented by plane stress elements and in situ joints by interfacial elements. Structural response of PS wall in the elastic zone has been studied in this paper. The effects of shear and normal stiffness of joints, member of vertical joints, separation of joints, gravity load and the effect of flexible foundation on the structural response have been investigated for a 12-storeyed PS wall.

INTRODUCTION

Recently large panel construction system has become common because of its numerous advantages over *in situ* shear wall construction system. Prefabricated jointed panel construction consists of single-storey high precast wall panels joined together by vertical *in situ* joints. The precast floor panels are laid over the already erected walls and the next storey of precast wall panels are placed with filling of *in situ* horizontal joints at floor level. This sequence of construction is followed till the whole building is completed. The structural scheme is generally cross-wall type and the longitudinal facade walls are constructed of precast wall panels of light weight concrete for better thermal insulation. Precast wall panels of dense concrete, which generally form the cross-walls, are designed to carry all lateral loads and thus behave as prefabricated shear walls.

Although lot of literature is available on structural characteristics of *in situ* shear walls, there is little information available for precast shear (PS) wall assembly. The *in situ* vertical and horizontal joints, which are much more deformable than precast wall panels, play an important role in determining the structural characteristics of PS wall. When a PS wall is subjected to lateral loads, the *in situ* joints in the precast wall assembly deforms to form slip surfaces. The stresses and deformation of the PS wall assembly, therefore, depend on the shear stiffness of such joints. The horizontal floor joints are, however, much more stiff as compared to the vertical wall joints due to the gravity load on horizontal joints and consequently high frictional resistance and also by the efficient and effective jointing of the top and bottom wall panels and floor panels. Hence, the response of PS wall under lateral load primarily depends on the flexible vertical joints.

The influence of various parameters such as shear stiffness of joints, gravity load effect; and soil structure foundation interaction effect of PS walls have been studied in this paper.

FINITE ELEMENT REPRESENTATION

Shear walls, when subjected to lateral loads due to wind or earthquakes, basically present a plane stress problem. Plane stress finite element formulation has been well documented in literature[1] and used by McLeod[2] and Girijavallabhan[3] for analysis of shear walls. Interfacial elements developed by Goodman, Taylor and Brekke[4] have been used successfully in the analysis of jointed rocks and other continuum problems with cracks, fissures of weak joints.

In this paper, precast wall panels in PS wall have been represented by plane stress elements and *in situ* joints by interfacial elements.

ILLUSTRATIVE EXAMPLE

A 9m wide and 36m high PS wall (12-storeys high) with a vertical joint in the middle has been analyzed. Shear stiffness of vertical joints has been taken as 1000 kg/cm^2 and the normal stiffness as very high. Details of the wall, including discretization of plane stress and interfacial elements, have been shown in Fig 1. The PS wall has been discretized into 36 elements in one case and 120 elements in the other. Considering the horizontal joints as rigid, only vertical joints have been

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discretized by interfacial elements. For all elastic analyses discussed in the paper, a uniformly distributed load of 5 kg/cm has been assumed. The deflection and shear stress diagram for the two cases have been shown in Figs 2 and 3(a), respectively. Deflection and joint shear stress have also been calculated from the formulae

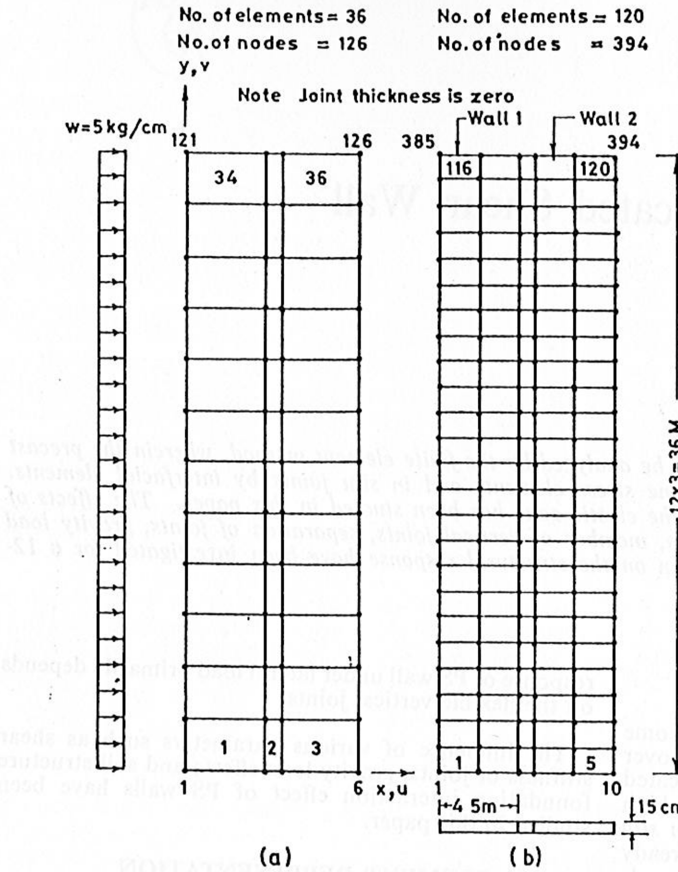

Fig 1 Finite element discretization of 36 m high 12-storeyed PS wall

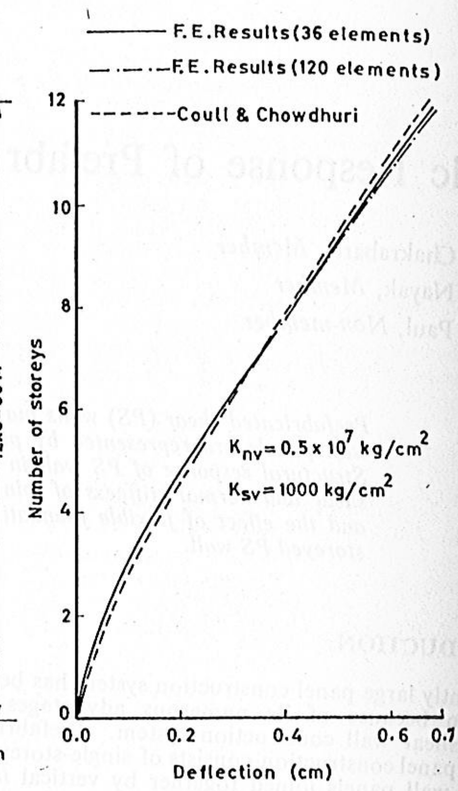

Fig 2 Comparison of deflection profile

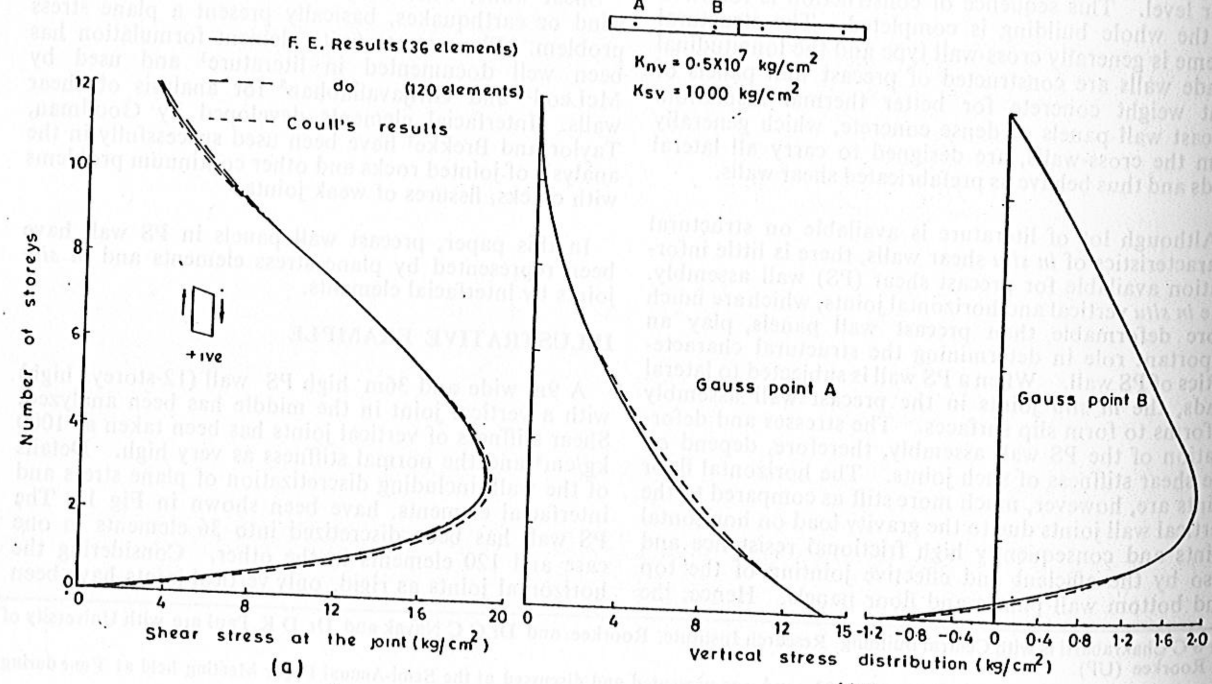

Fig 3 Comparison of stress distribution in 12-storey PS wall

given by Coull and Chowdhury[5]. It has been observed that the comparison is satisfactory. It is also evident that the storey-high discretization of elements is satisfactory. Coull and Chowdhury[5] have not considered shear deformation, whereas finite element discretization includes it. Hence, deflection, when found slightly higher than that obtained from Coull and Chowdhury, is justified. Distribution of vertical stresses at two critical sections has been shown in Fig 3(b) and compared with results given by Coull and Chowdhury[5]. The comparison is satisfactory.

EFFECT OF SHEAR STIFFNESS OF VERTICAL JOINTS

Fig 4(a) shows deflection of PS wall. If the infill material of the joint is infinitely stiff ($K_{sv} = K_{nv} = 0.5 \times 10^7$ kg/cm²), the two wall components may be considered as monolithically connected single solid cantilever wall of width 9 m. The elastic deflection of a 9 m deep cantilever wall has been shown in Fig 4(a) for comparison. On the contrary, if the infill material of the joint is loose and flexible ($K_{sv} = 0$), the PS wall may be considered to be consisting of two independent cantilever walls of depth 4.5 m each. Obviously, the deflection of such independent walls will be four times that of a monolithic wall. These might be treated as two limiting cases. The flexibility of PS wall will be within these limiting cases depending upon how efficiently the vertical joint is bonded with the infill material.

It may be observed from Fig 4(a) that the flexibility of PS wall increases as the shear modulus of the joint decreases. With an infinitely stiff joint (K_{sv}, K_{nv} very high), the structural response is almost the same as that of a monolithic single cantilever. As the value of K_{sv} is decreased, deflection of the wall increases. However, the advantage of reducing the deflection at the top by simply introducing a poor grade material is substantial, as can be noticed from Fig 4(a). Even when the shear modulus is as low as 50 kg/cm², the lateral deflection at the top is about 55% of the top deflection of two independent walls, where the vertical joint between the two prefabricates is not connected at all.

The ratio of the deflection of PS wall to that of a solid cantilever wall gives an indication of increased flexibility of PS wall as compared to a cantilever wall. The ratio along the height of PS wall for three different values of K_{sv} ($K_{sv} = 0.5 \times 10^7$, 1000 kg/cm² and 50 kg/cm²) has been plotted as an inset in Fig 4(a). It may be observed that the increase in comparative flexibility is more towards the bottom.

Fig 4(b) shows the horizontal displacement of PS wall on both sides of the joint, that is, deflection of both the wall panels for different combinations of K_{sv} and K_{nv} values. It may be noticed that when K_{nv} is high (0.5×10^7 kg/cm²), deflection of the wall panels on two sides of the joint are equal. In case of a low K_{nv} value ($K_{nv} = 50$ kg/cm²), the windward wall panel (wall panel 1) deflects more as compared to wall panel away from the windward side (wall panel 2), thereby squeezing the joint material. Also, lateral deflection of PS wall is affected only by K_{sv} and little by K_{nv}.

Distribution of shear stress in the vertical joint is presented in Fig 5(a) for different values of K_{sv}. It is observed that shear stress distribution along the vertical joint varies with the values of K_{sv}. The position of maximum shear stress also changes as shown in the figure.

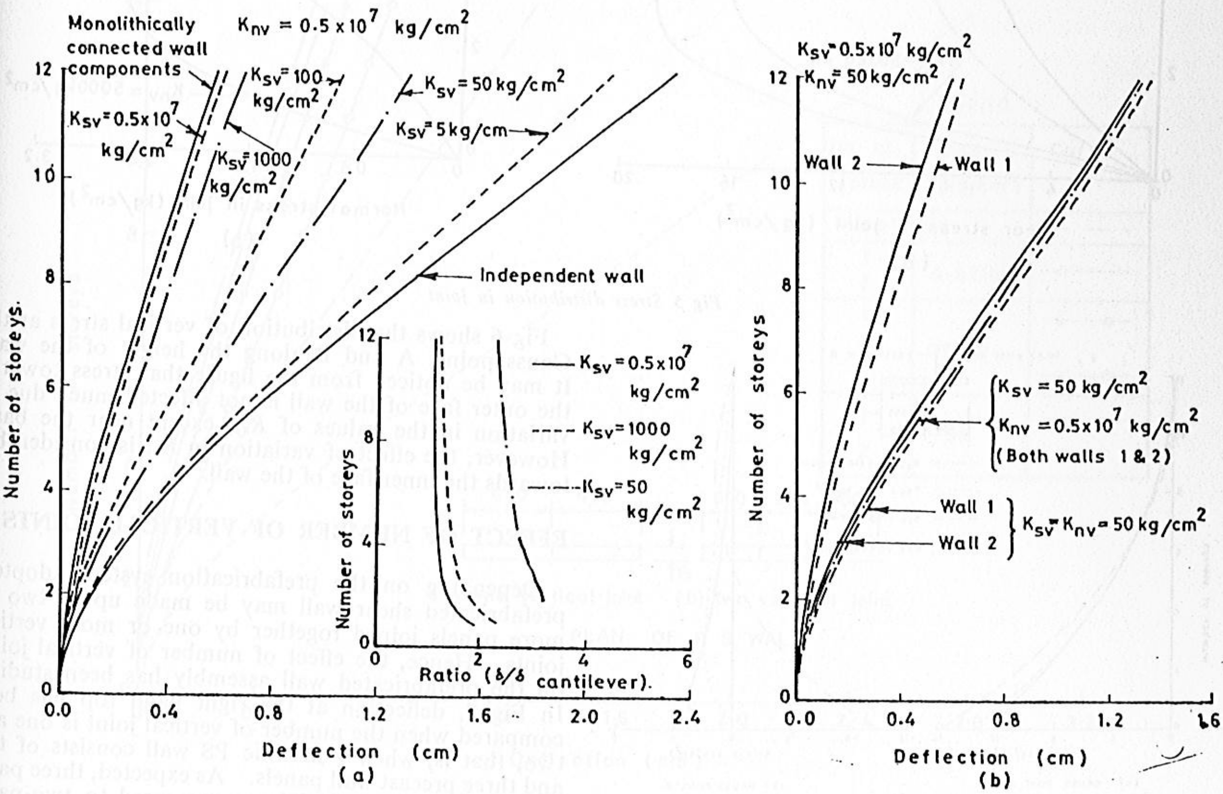

Fig 4 Lateral deflection of 12-storey PS wall

The change in the values of shear stress along the joint is more rapid in case of high shear rigidity of joints, and smooth and slow for low values of K_{sv}.

Since the constitutive law matrix of interfacial elements representing the joint is diagonal (neglecting cross coupling terms), the values of shear stress do not change with variation in the values of K_{nv}. Similarly, the values of normal stress in the joint do not change with variation in K_{sv}.

Fig 5(b) shows the distribution of normal stress along the joint for two values of K_{nv}, a moderately high value of 5000 kg/cm² and a low value of 50 kg/cm². It is observed that normal stress is slightly higher near the top for a low value of K_{nv}.

The effect of K_{nv} on the normal stress distribution clearly indicates the interaction of two wall panels. For large value of K_{nv}, the share of normal load is almost equal for upper ten-storeys of the wall. However, for the bottom two storeys, wall 1 carries more load because of application of the load on the outer face of wall 1. For lower value of K_{nv}, wall 1 carries more load in the bottom storeys as compared to wall 2, whereas in the top storeys wall 2 carries more load as compared to wall 1. This behaviour can be predicted only by finite element analysis. It may be mentioned that in the shear continuum theory based on beam theory, the load is assumed to be applied at the centroidal axis of the shear wall, and the horizontal stresses, σ_n, and the corresponding deformation is completely neglected.

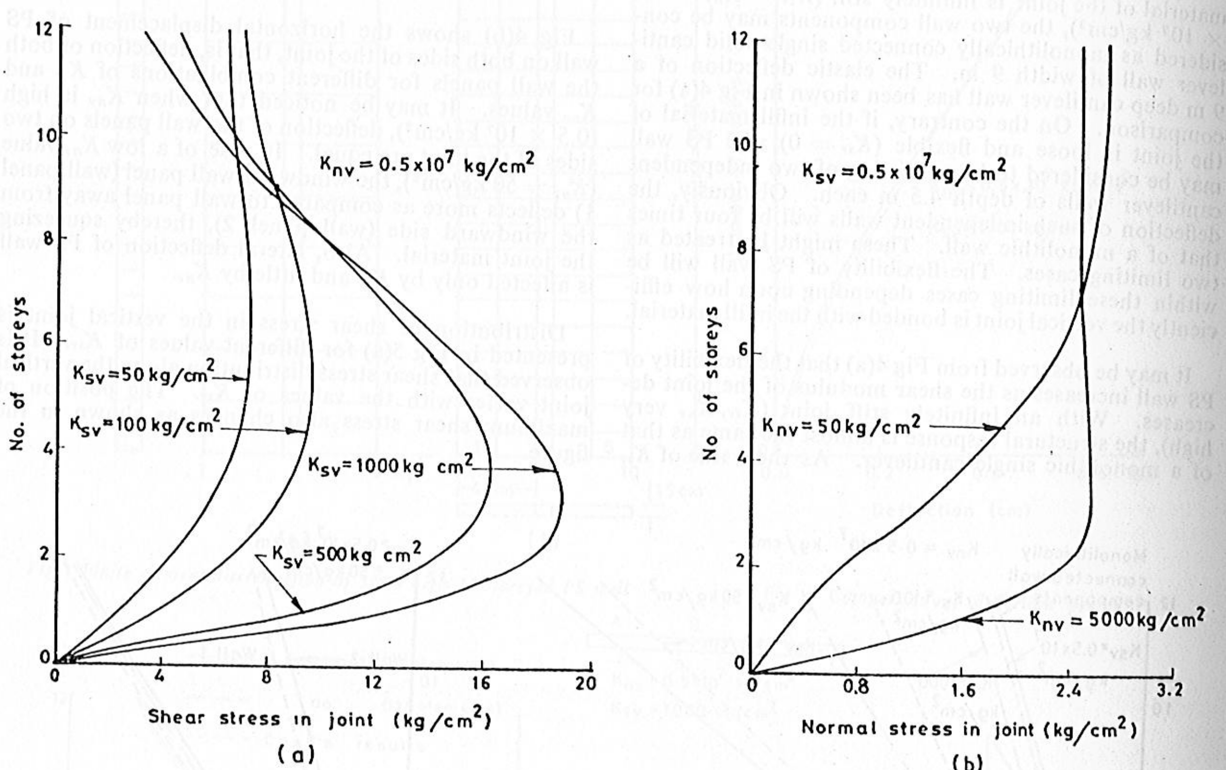

Fig 5 Stress distribution in joint

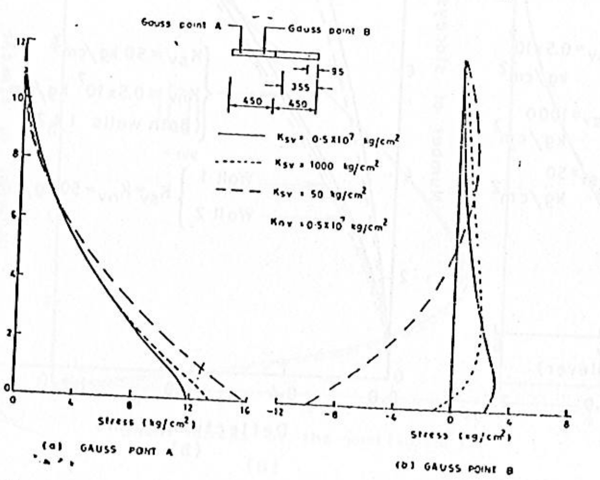

Fig 6 Vertical stress distribution in wall panels of 12-stores PS wall

Fig 6 shows the distribution of vertical stress at the Gauss points A and B along the height of the wall. It may be noticed from the figure that stress towards the outer face of the wall is not affected much due to variation in the values of K_{sv}, except near the base. However, the effect of variation in K_{sv} is considerable towards the inner face of the wall.

EFFECT OF NUMBER OF VERTICAL JOINTS

Depending on the prefabrication system adopted, prefabricated shear wall may be made up of two or more panels joined together by one or more vertical joints. Hence, the effect of number of vertical joints on the prefabricated wall assembly has been studied. In Fig 7, deflection at the right hand top has been compared when the number of vertical joint is one and two, that is, when 9 m wide PS wall consists of two and three precast wall panels. As expected, three panel shear wall is more flexible as compared to two-panel shear wall for low values of K_{sv}. However, when the value of K_{sv} is infinitely high, the joints do not provide shearing media of any significance and the PS wall whether it is made of two or three panels behaves in a similar fashion as observed from the overlapping of the two deflection curves.

The distribution of shear stress in the two joints along the height of the three-panel PS wall is shown in Fig 8(a). They are found to be same in both the joints. The normal stress distribution in the two joints are shown in Fig 8(b). It may be observed that the normal stress in the vertical joint nearer to the loaded face carries higher normal stress than the joint at the farther end. The normal stresses are not proportionately shared by the three panels as can be seen from Fig 8(b).

SEPARATION IN JOINT

Bond at the interface of infill joint and the precast wall panel is not generally satisfactory and development of tension in the joint may lead to separation at the interface. Hence, the effect of separation in the joint was studied.

Suitable modifications were incorporated in the computer program to account for such eventuality. Separation is considered to occur when tensile stress in the joint reaches a limiting value. As soon as tensile stress at any of the sampling points exceeds the critical tensile stress, the value of K_{sv} and K_{nv} will be assigned suitable low values and the stresses σ_s and σ_n at that sampling point will be taken as zero. This, in turn, disturbs the equilibrium and hence stress redistribution will take place with further iterations to re-establish the equilibrium. Such a modelling will give a true picture of the stress configuration in PS wall. The analysis is truly nonlinear since with the onset of separation at the joint, the value of K_{sv} is taken from the nonlinear shear stiffness slip relationship.

$$K_{st} = C_1 + C_2 s + C_3 s^2 \quad (1)$$

where C_1, C_2 and C_3 are arbitrary constants. These constants depend on various parameters (material properties, types of joint, reinforcement, workmanship, etc). For this study, following nonlinear relationship has been taken:

$$K_{st} = 1000 - 7260\,s$$

subject to a minimum value of $K_{st} = 5$ kg/cm².

The value of normal stiffness K_{nv} is taken as a fixed specified value ($K_{nv} = 5000$ kg/cm²). When separation takes place at any sampling point in the vertical joint, K_{nv} assumes a minimum specified value. On closing of the separation, K_{nv} again assumes the original value. Critical tensile stress, when separation takes place, has been assumed as 0. Values of K_{sv} and K_{nv} on separation have been taken as 5 kg/cm².

Deflection, shear and normal stress distribution in the joint for both the cases, that is, with and without separation at the joint are plotted in Fig 9. It is observed

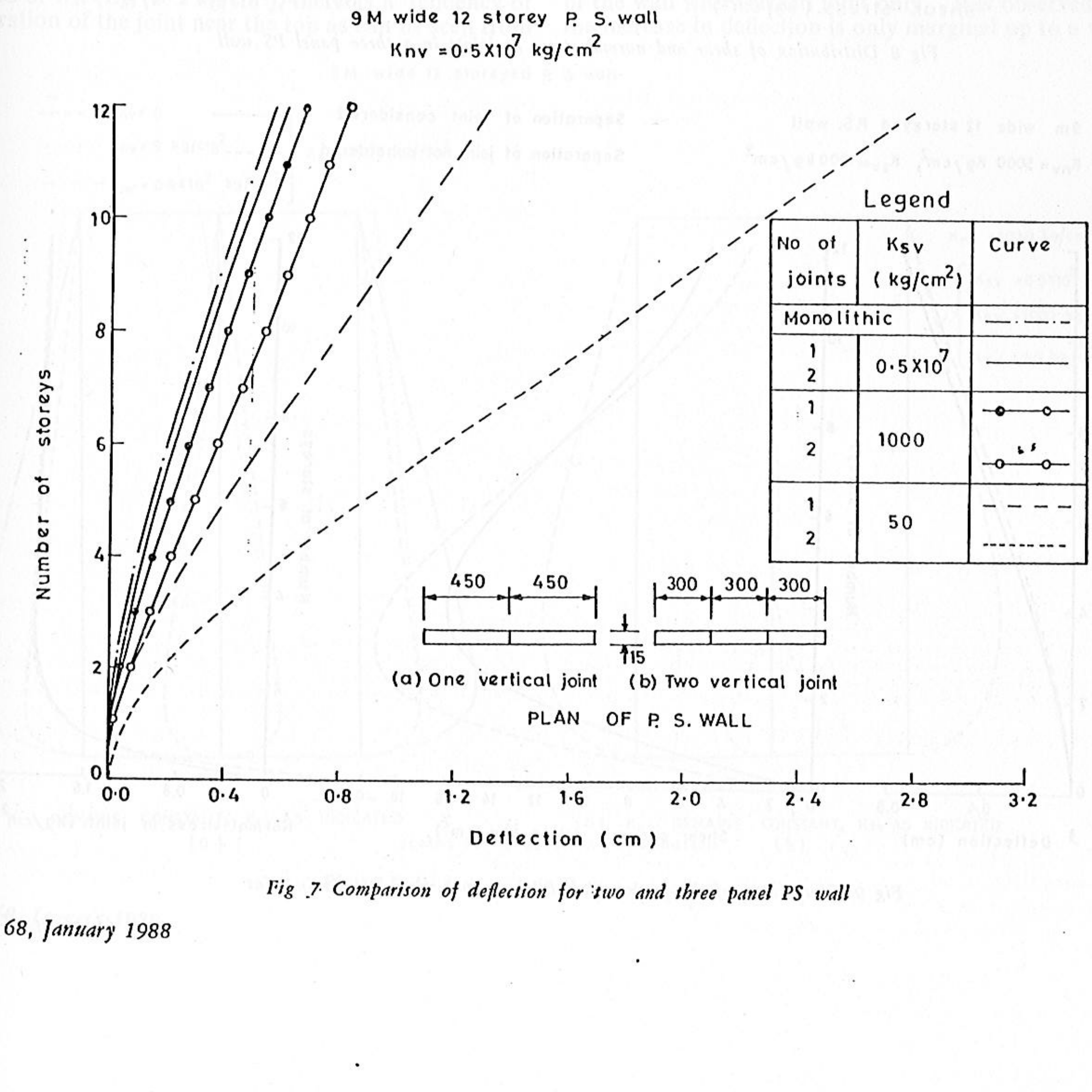

Fig 7 Comparison of deflection for two and three panel PS wall

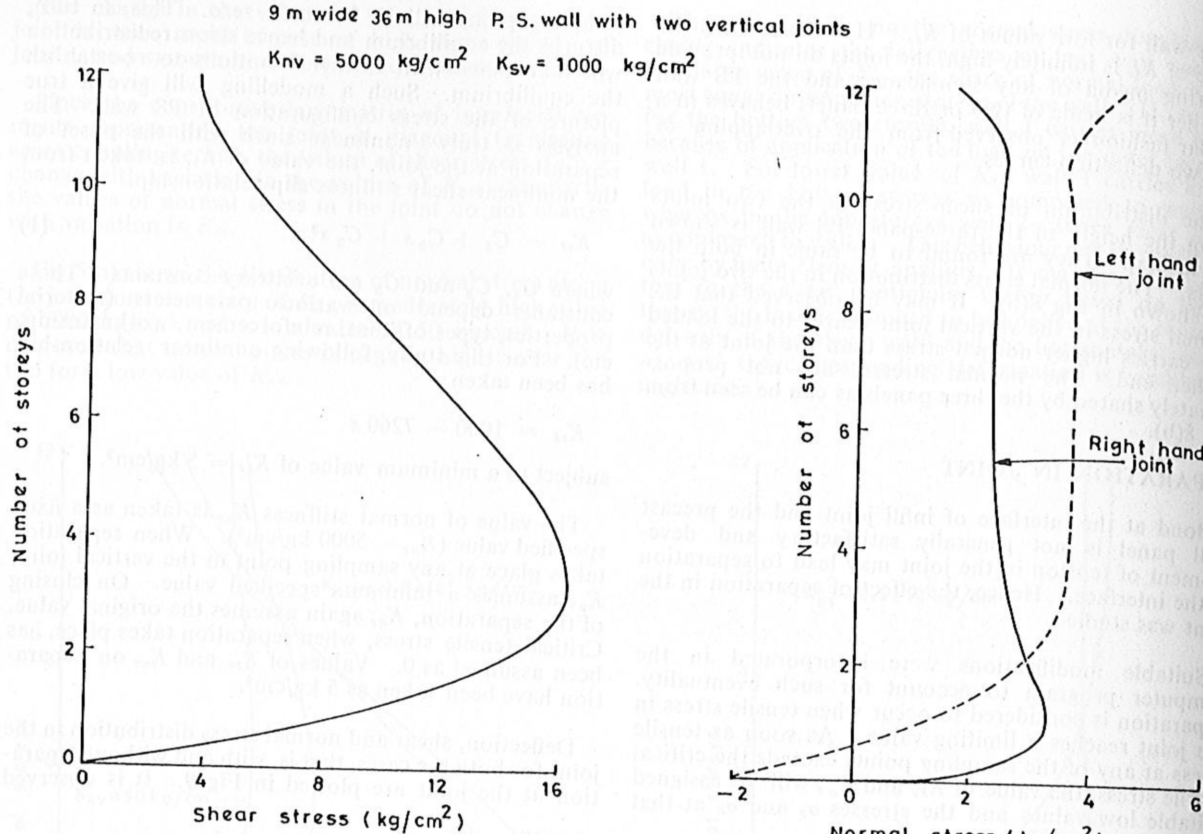

Fig 8 Distribution of shear and normal stress in joints in a three panel PS wall

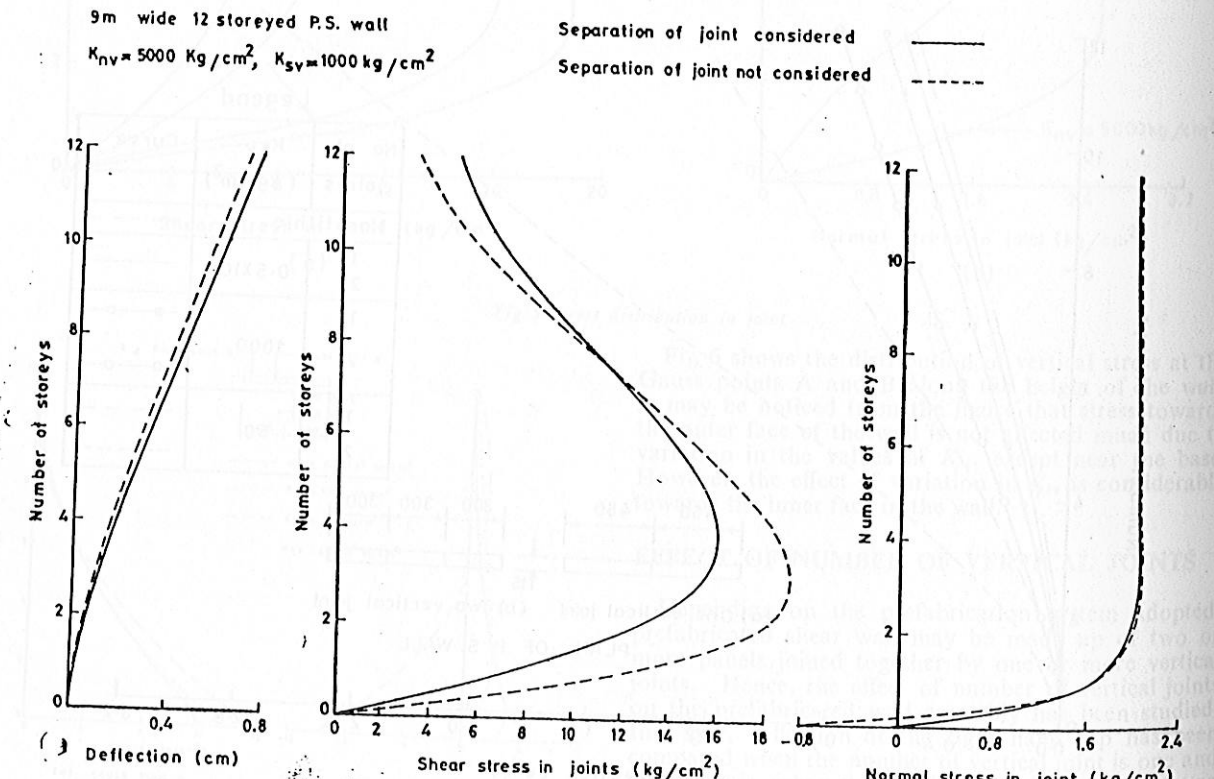

Fig 9 Comparison of displacement shear stress and normal stress in joint

that if separation at the joint is considered, deflection of PS wall increases. This increase will, however, depend on the non-linear slip shear stiffness relationship to a great extent. For the case analyzed, this increase is marginal, but in certain cases it can be substantial.

It may also be observed that shear stress in the joint reduces due to separation in the joint. Also, the analysis without allowing any tension to develop in the joint eliminates the tensile normal stress in the vertical joint observed near the base and makes the normal pressure compressive throughout the height of the wall.

RESPONSE UNDER GRAVITY LOAD

The same 12-storeyed PS wall has been analyzed for its own weight and the deformed shape has been studied for the following two cases:

(i) When K_{sv} remains constant and K_{nv} varies [Fig 10(a)], and

(ii) When K_{nv} remains constant and K_{sv} varies [Fig 10(b)].

Fig 10(a) shows the deformation of PS wall in X-direction at the outer edges and at the interface. It is found that the deformation in X-direction depends on K_{nv}. When K_{nv} is very high ($K_{nv} = 0.5 \times 10^7$ kg/cm²), the PS wall behaves like a monolithic 9 m wide PS wall. When $K_{nv} = 0$, the PS wall behaves as if the wall components are two individual walls. These have been verified by the deformation of a 9-m wide and 4.5-m wide cantilever wall under its own weight. For low values of K_{nv} ($K_{nv} = 5$ kg/cm²), there is a tendency of separation of the joint near the top as can be seen from Fig 10(a). However, with increase in K_{nv} values, the separation tendency at the joint tends to vanish.

It is observed that lateral deformation of PS wall both at the outer edges and the interface remains same irrespective of the shear stiffness values of joints [Fig 10(b)]. Thus, K_{sv} has not got any appreciable influence on the lateral deformation of PS wall under its own weight.

EFFECT OF HORIZONTAL JOINTS

The horizontal joints at floor level of PS wall has been assumed to be stiff which may not be really true since there may be some construction where due to improper quality of work or due to bad joint detailing, the horizontal joints may be flexible.

In order to study the effect of flexible horizontal joints, a 9-storeyed and 36 m high and 9 m wide two panel PS wall has been studied.

The shear stiffness of horizontal joints (K_{sh}) has been varied keeping other joint stiffness properties constant ($K_{nh} = K_{nv} = 0.5 \times 10^7$ kg/cm², $K_{sv} = 1000$ kg/cm²).

The deflection of 9-storeyed PS wall has been compared with and without flexible horizontal joints in Fig 11(a). It is observed that a PS wall having only flexible vertical joint and no horizontal joint is always stiffer in its behaviour. The deflection diagram with high values of stiffness of horizontal joints ($K_{sh} = K_{nh} = 0.5 \times 10^7$ kg/cm²) approaches the deflection diagram of the wall with vertical joint only. It is observed that the increase in deflection is only marginal up to a value

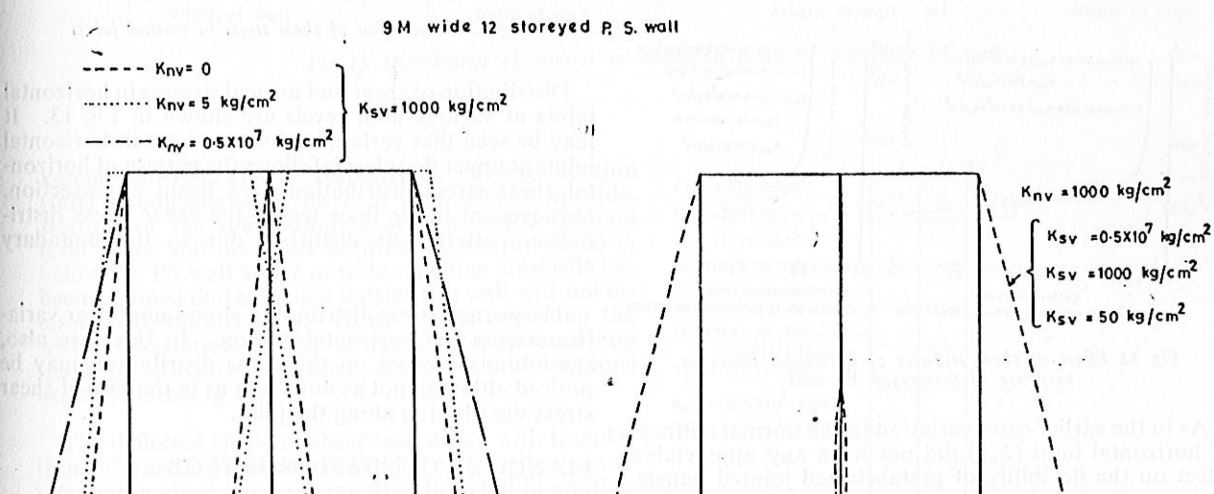

Fig 10 Deformation of PS wall under gravity load

of K_{sh} equal to 2000 kg/cm² and for lower values of K_{sh}, the increase in deflection is considerable [Fig 11(b)].

Slip at the horizontal joint is negligibly small even up to a value of K_{sh} = 1000 kg/cm². However, considerable slip is observed at the floor levels for lower values of shear stiffness [K_{sh} = 100-50 kg/cm², Fig 11(a)]. It is fortunate that such low values of K_{sh} as to cause significant slip at the floor level are not expected in actual practice.

The top deflection of PS wall for various values of K_{sv} in the vertical joint and K_{sh} = 1000 kg/cm² in the horizontal joint is shown in Fig 11(c). The values of normal stiffness (K_{nh} = K_{nv} = 0.5 × 10⁷ kg/cm²) remain constant. As may be observed, the increase in maximum deflection is almost uniform for all values of shear stiffness, K_{sv}. In practical situations, however, K_{sh} will always be greater than K_{sv} and the increase in deflection due to the flexibility of horizontal joints will be insignificant.

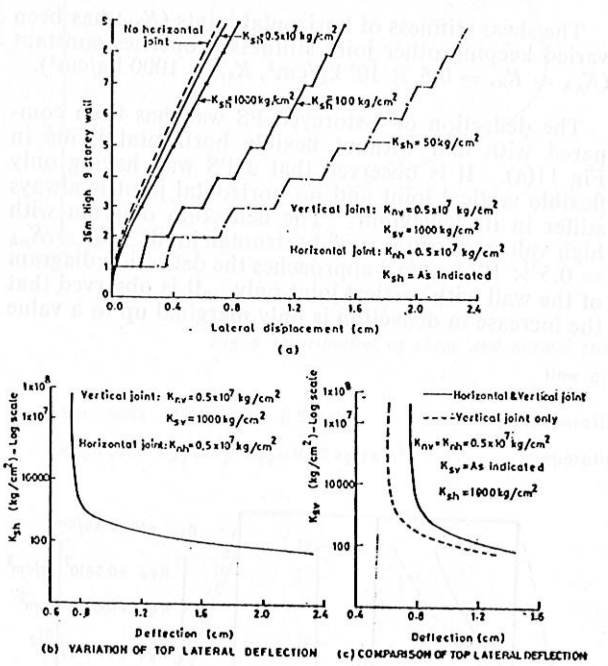

Fig 11 Effect of shear stiffness of horizontal joints in response of 9-storeyed PS wall

As in the earlier case, variation in the normal stiffness of horizontal joint (K_{nh}) did not have any appreciable effect on the flexibility of prefabricated jointed panels.

The shear stress distribution in the vertical joint of 9-storeyed PS wall has been given in Fig 12(a) for two cases:

(i) With vertical joint only (K_{nv} = 0.5 × 10⁷ kg/cm² and K_{sv} = 1000 kg/cm²);

(ii) With both horizontal and vertical joints (K_{nv} = K_{nh} = K_{sh} = 0.5 × 10⁷ kg/cm² and K_{sv} = 1000 kg/cm²). It is observed that there is no appreciable change in the value of maximum shear stress in the vertical joint, except that there is an upward shift in the location of maximum shear stress.

Fig 12(b) shows the influence of the shear stiffness of horizontal joints, K_{sh}, on the distribution of shear stress in the vertical joint. It is observed that as the value of K_{sh} decreases, the value of maximum shear stress increases marginally without any marked shift in the location of the point of maximum shear stress.

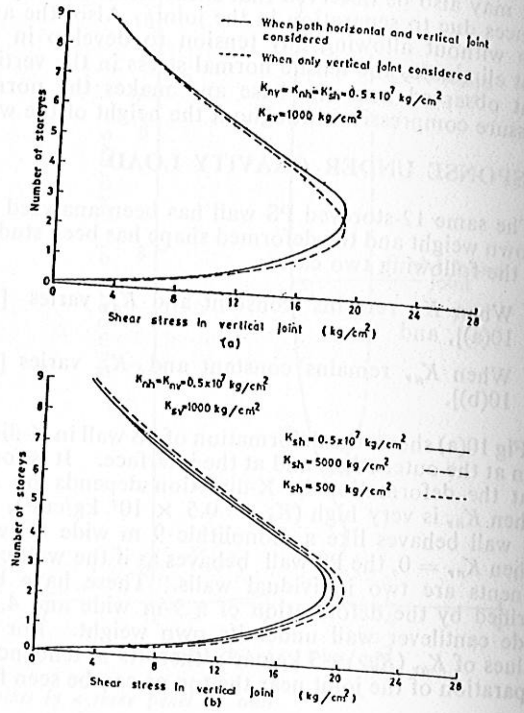

Fig 12 Distribution of shear stress in vertical joints

Distribution of shear and normal stresses in horizontal joints at various floor levels are shown in Fig 13. It may be seen that variation of shear stress in horizontal joints at upper floor levels follows the pattern of horizontal shear stress distribution in a beam cross-section. However, at lower floor levels, the shear stress distribution pattern gets disturbed due to the boundary effect.

The normal stress distribution shows nonlinear variation across the horizontal section. In this case also, the boundary effect on the stress distribution may be noticed although not as dominant as in the case of shear stress distribution along the joint.

FLEXIBLE FOUNDATION EFFECT

The PS wall has been assumed to have full restraint at the base. However, the foundation with soil mass within the influence zone below the foundation also deforms along with the superstructure.

In the finite element representation of soil foundation system, soil has been assumed to be linear isotropic material. The modulus of elasticity of the soil mass has been assumed to vary from 200 kg/cm² to 20 000 kg/cm² so that the modulus ratio E_c/E_{soil} varies from 1000 to 10.

The same 9-m wide 12-storeyed and 36-m high PS wall has been taken for this study. Only the vertical joint has been considered for the analysis and the values of K_{nv} and K_{sv} have been assumed to be 0.5 × 10⁷

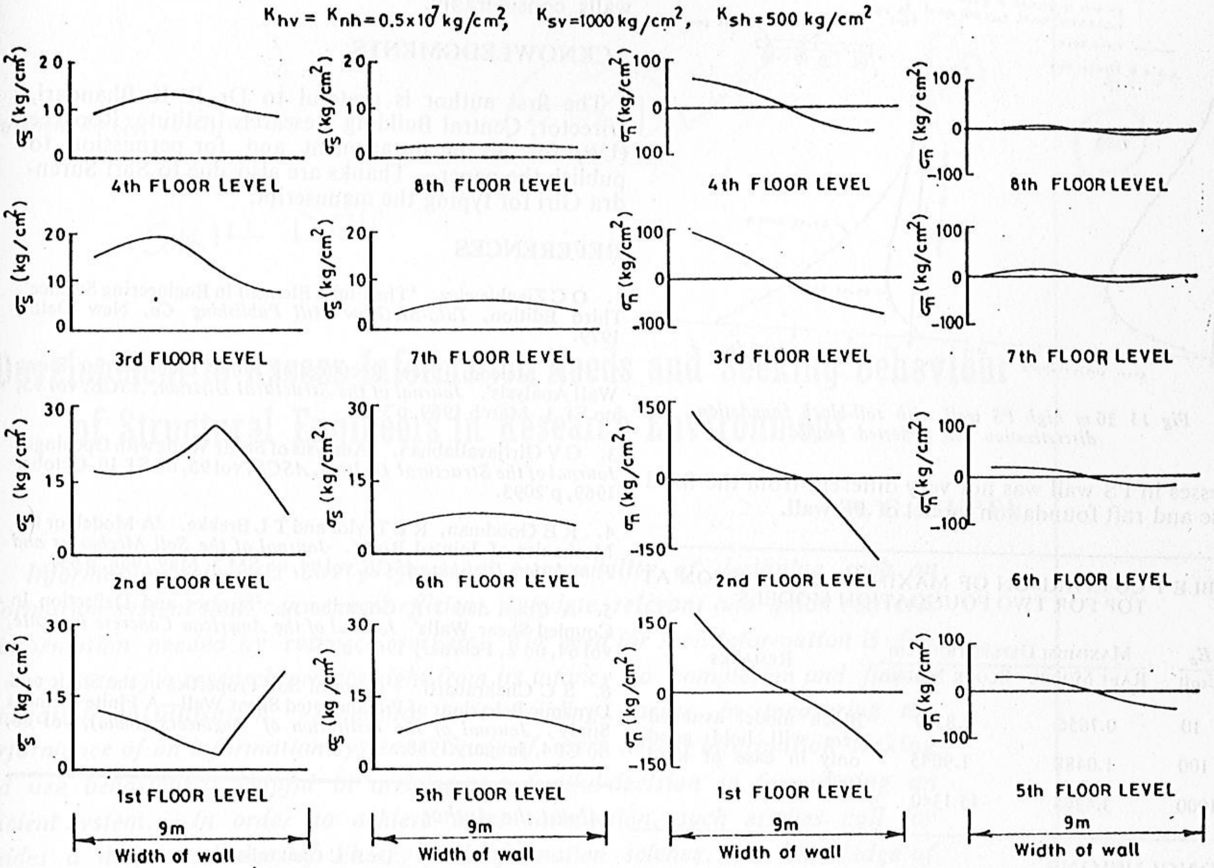

Fig 13 Distribution of stresses in horizontal joints of 9-storeyed PS wall

kg/cm² and 1000 kg/cm², respectively. The foundation (raft) is considered to be 1 m deep and 7 m wide. Bottom of the foundation is at 3 m below ground level. The soil mass has been considered up to 20 m below the PS wall and 7 m wide on either side. It has been assumed that soil mass outside this wall will not interact with the structure. Other details regarding the with discretization of the soil foundation system along the superstructure and their geometrical dimensions are shown in Fig 14.

The deflected shape of shear wall along with foundation deformation is shown in Fig 14. The soil structure interaction effect has been reported in detail in another paper[6].

Block Type Foundation

In another analysis, the soil foundation system has been modelled in a different way as shown in Fig 15. In this case, foundation of PS wall has been assumed to be 40 cm thick and 2 m deep below the base level. The width of soil mass to interact with the foundation and superstructure is assumed to be 2 m. The depth of soil mass is 20 m below the ground. It was found that for the same value of E_c/E_{soil}, the deflection of PS wall is substantially more than the soil structure model (raft foundation model) adopted earlier. When $E_c/E_{soil} = 1000$, maximum deflection at top was more than 15 cm, which is not permissible. The comparison of maximum deflection at top is as given in Table 1. However, the

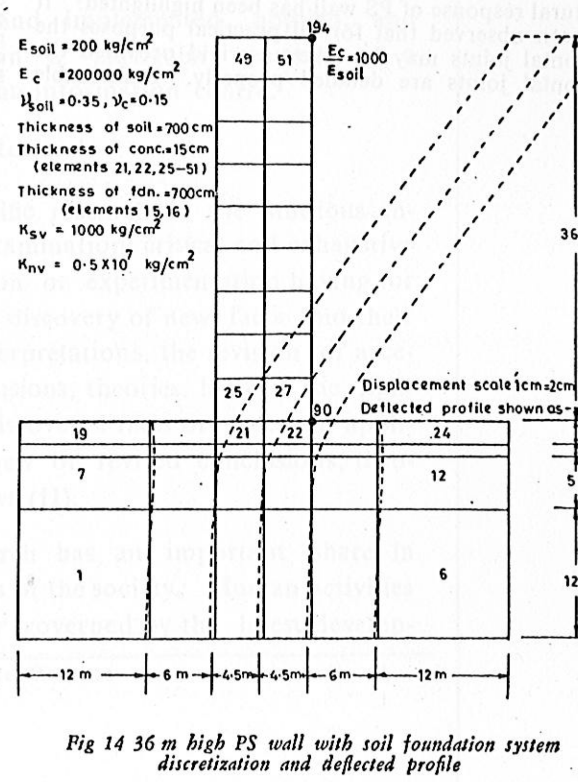

Fig 14 36 m high PS wall with soil foundation system discretization and deflected profile

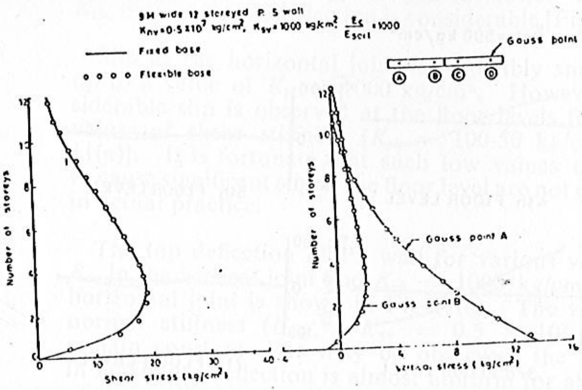

Fig 15 36 m high PS wall with soil-block foundation discretization and deflected profile

stresses in PS wall was not very different from the fixed base and raft foundation model of PS wall.

TABLE 1 COMPARISON OF MAXIMUM DEFLECTION AT TOP FOR TWO FOUNDATION MODELS

$\frac{E_c}{E_{soil}}$	Maximum Deflection, cm		Remarks
	Raft Model	Block Model	
10	0.7656	0.8347	Block model assumed here will hold good only in case of hard rock
100	1.0488	1.9045	
1000	3.4365	15.1340	

CONCLUSIONS

The paper uses plane stress and interfacial elements for study of structural behaviour of prefabricated shear wall. The importance of shear stiffness of joints in the structural response of PS wall has been highlighted. It has been observed that for all practical purposes the horizontal joints may be taken as rigid provided the horizontal joints are detailed properly. Deformable soil foundation system increases the flexibility of PS walls considerably.

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