EARTHQUAKE-RESISTANT DESIGN THEORY FOR PREFABRICATED STRUCTURES USING CHECKERED SHEAR WALL FRAMES

by

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SYNOPSIS

The authors are engaged in research on an earthquake-resistant prefabricated building system allowing much freedom in architectural planning and backed by wide-range experimentation with the chief aim of application to multi-storied apartment house construction. The basis of this system is an earthquake-resistant element structured by shear walls reinforced around their peripheries by frames and positioned three-dimensionally in a checkered pattern. The paper describes a practical and highly accurate elastoplastic analysis method for this checkered shear wall frame and the method of earthquake-resistant design for the frame illustrated by an actual case of a 14-storied building.

1. OUTLINE OF SYSTEM AND CHARACTERISTICS OF CHECKERED FRAMES

This research considers an elastoplastic analysis method and concrete design method for checkered shear wall frames incorporated inside dwelling units as frameworks for prefabricated multi-storied apartment house buildings. The basic concept is indicated in Fig. 1-1.

That frames with walls are advantageous for earthquake resistance has been recognized in the past each time a major earthquake has occurred and walls are being adopted today in earthquake-resistant design of practically all highrise buildings. As for dwellings, because of their functions they are buildings intrinsically high in the proportions of walls, and if the locations of the walls could be adjusted and systematized, it would be possible for applications to be made to a variety of housing plans utilizing the walls to the utmost for earthquake resistance.

It has been attempted to apply checkered shear wall frames architecturally from the standpoint of such thinking. And it has been verified by experiments conducted at the laboratory with which the authors are affiliated that checkered shear wall frames possess superior strengths. Furthermore, since field jointing in prefabricated construction with this framing system is limited only to intersecting points of corners where walls are connected, it is possible for wall panels to be manufactured monolithically with upper and lower beams (and left and right columns) at the factory for extremely good efficiency and a high degree of safety as well.

2. ELASTOPLASTIC ANALYSIS METHOD FOR CHECKERED SHEAR WALL FRAMES

2-1. Outline of Analysis Method

Normally, in analyses of walled frames, it is the practice for the walls to be simplified into line members such as braces. In the case of elastoplastic analysis, when walls are simplified into braces the analysis is carried out taking into account the rate of reduction in stiffness

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aginst shearing, but it is very difficult to carry out analysis considering also the rate of reduction in flexural stiffness of walled columns at the same time. It is possible for an even more accurate analysis to be made if the finite element method is employed, but to introduce this method in full to a large-scale frame is not realistic from the standpoints of such matters as time required for calculations. The authors therefore have tried a method of elastoplastic analysis taking advantage of the characteristics of checkered frames which is practical, and moreover, highly accurate.

Since in a checkered frame wall panels which comprise the units are connected to each other only at their corners, it is possible to consider the frame as being composed of unit walls with each as a finite element having displacements (u, v) of the four points and joint translation angles (θ) as unknowns. A unit wall as a single finite element is evaluated in the form of its stiffness reduced to u, v and θ at the four corner points through finite elements which have been further minutely divided beforehand. In case of performing elastoplastic analysis, the cracking conditions of unit walls in experiments are considered, and this stiffness matrix is determined only for a finite number of deformation stages. The element matrices expressed for the four corner points obtained are superposed one on another for analysis of the entire frame and through changing of these elastoplastic matrices by checks made at each calculation step it is possible to readily carry out elastoplastic analysis even for an actual structure of large size.

2-2. Example of Elastoplastic Analysis

(1) Analysis Model

The method of analysis is explained taking an analysis model of five stories and four spans (Fig. 2-1) as an example. It may be noted that this 5-storied, 4-span analysis model is identical to the model in the experiments conducted at the laboratory of the authors.

(2) Elastoplastic Element Matrix

With the results of experiments on unit walls conducted at this laboratory(1) as reference, the influence of overall bending deformation are put in and classification into the patterns as shown in Table 2-1 is carried out. For Young's moduli the secant moduli corresponding to the conditions of unit strains of walls and columns are adopted. The contribution to stiffness made by wall reinforcement is omitted in this case because of insignificant effect.

(3) Calculation Steps

A concentrated force P is acting at the top of the 5-storied, 4-span checkered frame. The joint translation angle due to horizontal displacement of the wall at the bottommost story is considered equivalent to the joint translation angle (R) in Table 2-1 and calculations are made for the following four steps:

- Step I $R \leqq 0.25\times10^{-3}$, all walls of pattern I in Table 2-1.
- Step II $R \leqq 1.0\times10^{-3}$, selection of appropriate element matrix from pattern II of Table 2-1 referring to unit strain in the axial direction of each walled column obtained in Step I.
- Step III $R \leqq 2.0\times10^{-3}$, the same procedure as in Step II followed for pattern III of Table 2-1.
- Step IV $R \leqq 4.0\times10^{-3}$, the same procedure as in Step II followed for

pattern IV of Table 2-1.

In case of analysis of an actual structure, the form of load distribution of each story is kept constant for all of the steps. Control of the steps is done with the average value of horizontal displacements of the walls at the bottommost story.

(4) Deformation Graph and Load-Deformation Curve

Fig. 2-2 indicates the states of deformation of the walls analyzed for the various steps. By connecting the horizontal displacements of these steps an envelope curve is obtained for the load-displacement curve (Fig. 2-3). There is also good agreement with experimental values.

3. EARTHQUAKE-RESISTANT DESIGN METHOD

3-1. Structural Planning

When carrying out structural design using this system, it is necessary for the structural designer to consider how ingeneously he should adopt the checkered shear wall frame to the architectural design and equipment plans. This framing system has been applied to various buildings from plate types to tower types and the case of a 14-storied plate-type prefabricated apartment house actually constructed is indicated in Figs. 3-1, 3-2 and 3-3. In case of a plate-type structure it is possible to arrange piles at the periphery without producing exorbitant stresses at inner portions by taking advantage of the special characteristics of a checkered frame such as the one shown in Fig. 1-1. This is extremely effective against overturning of the building. Further, when checkered walls are to be provided in the transverse direction as in this example, the position of the checkered shear wall frame in the longitudinal direction is to be kept from being out of line from the middle point of the transverse side to prevent disarrangement of the stiffness distributions in the vertical and transverse directions. Also, while adequately reinforcing unit shear walls with frames to secure strength and ductility, a tall shape of ratio of height divided by length greater than 1 is to be avoided.

3-2. External Forces during Earthquake and Design Stress

Computation of design stresses are to follow the earthquake provisions in the building code of the appropriate country (in case of Japan, base shear coefficient (C_B) is 0.2∿0.23 when the height of the building is not more than 45 m), and ultimate strength design is carried out for unit walls multiplying the above value by a certain load factor. This load factor is determined in a manner that the ultimate strength of the wall is not less than the response shear force in dynamic studies, but a value of 1.5 is normally considered.

When dynamic analyses are to be made, the sizes of earthquake waves must be determined giving thorough consideration to the seismicity of the particular region. Restoring force characteristics are evaluated tri-linearly through a combination of the analysis value obtained by the method in 2. and the ultimate load-carrying capacity of the wall. As for open frames at the periphery, an elastic design satisfying stresses corresponding to response displacements obtained from the dynamic analyses is carried out.

3-3. Ultimate Strength of Shear Wall(1)

The principles for calculation of ultimate strength of a shear wall reinforced at its periphery by a frame will be as described below.

(1) The maximum shearing resistance of the wall is determined from its failure mechanism by the lesser of either the sum of the bearing capacities of the diagonal braces, shear reinforcement of the wall, and the peripheral frame of the wall, or the sum of the bearing capacities of the diagonal braces, the shear reinforcement of the wall, and wall concrete.

(2) The shearing resistance of a diagonal brace is given by the following equation: $_b\tau = 2\,{}_bA\,{}_b\sigma \cos\theta \sin 2\theta / tl$

where $_bA$: cross-sectional area of brace on one side
$_b\sigma$: yield strength
θ: angle with beam frame
tl: horizontal cross section of wall

(3) The resistance of shear reinforcement of the wall is given by the following equation: $_r\tau = p_s \sigma_y$

where p_s: shear reinforcing bar ratio of wall
σ_y: yield strength of shear reinforcement of wall

(4) The resistance of wall concrete is given by the following equation: $_c\tau = 0.2\,F_c - 0.5\,{}_r\tau$

where F_c: compressive strength of wall concrete

BIBLIOGRAPHY

(1) Imai, H., Yokoyama, M., and Sonobe, Y., "Behavior of Framed Shear Walls under Shear Load (11-33)", Proc. 6 WCEE, New Delhi, 1977.

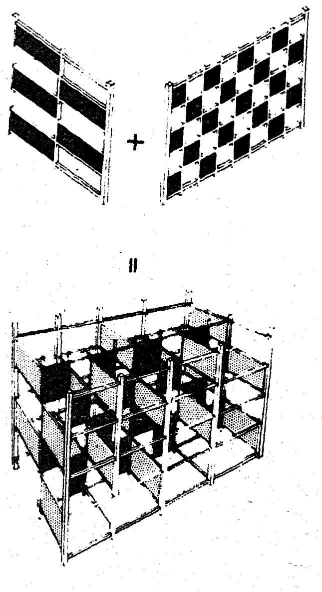
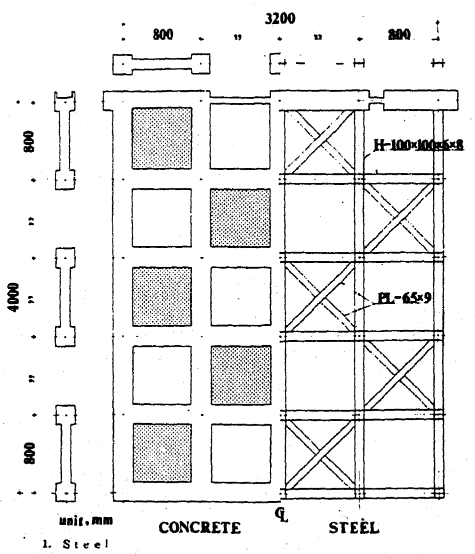
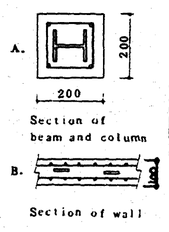


Fig1-1 Component of fundamental unit





1. Steel

	Reinforcement	size (mm)	Steel ratio	material
A	Steel	H-100×100×6×8	5.48 (%)	SS41*
	reinforcing bar	13 (plain)	1.33	SR24*
	Stirrup, hoop	6 (plain) @100	0.28	SR24*
B	Steel	PL - 65×9	1.03	SS41*
	reinforcing bar	6 (plain) @100	0.56	Welded Wire*

* Standardized by JIS

2. Concrete
- light weight concrete
- compressive strength = 210 kg/cm²

Fig2-1 Analysis model

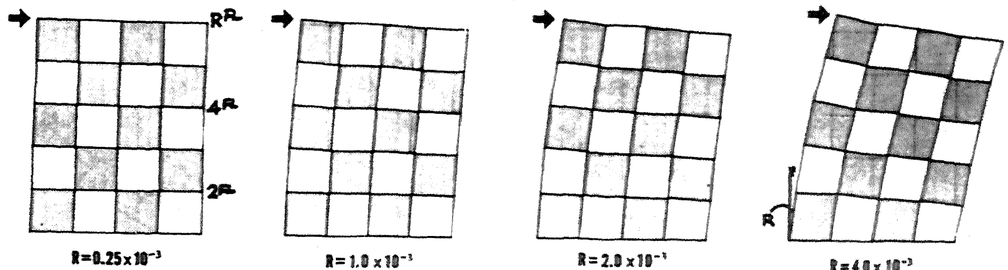


Fig2-2 Progress of analyzed deformation

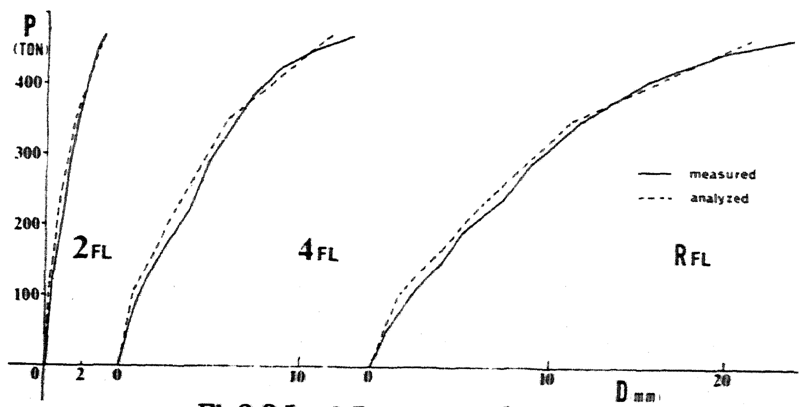
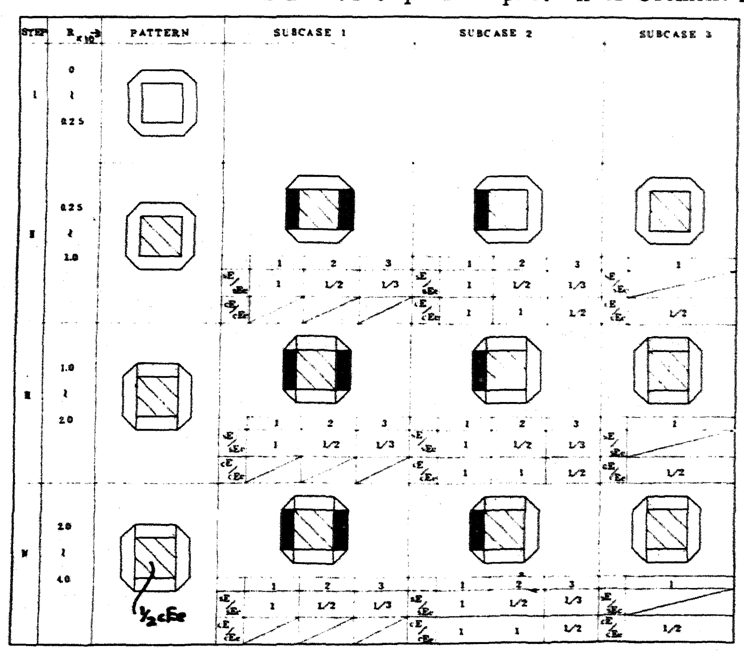


Fig2-3 Load-Deflection Curve

Table2-1 Elasto-plastic pattern of element matrices



1 Relation of sE/sEc ~ ε

ε	0~0.15	0.15~0.3	0.3~
sE/sEc	1	1/2	1/3

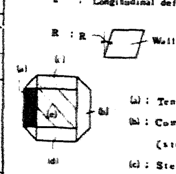
2 Relation of cE/cEc ~ ε

ε	0~0.2	0.2~
cE/cEc	1	1/2

Where,

- sEc : Young's Modulus of steel (2100 t/cm²)
- cEc : Young's Modulus of concrete (140 t/cm²)
- sE : Secant Modulus of steel in tension column
- cE : Secant Modulus of concrete in compression column
- ε : Longitudinal deformation for column (%)

R : R



- (a) : Tension Column (steel)
- (b) : Compression column (steel and concrete)
- (c) : Steel (elastic)
- (d) : Steel and concrete
- (e) : Crack line

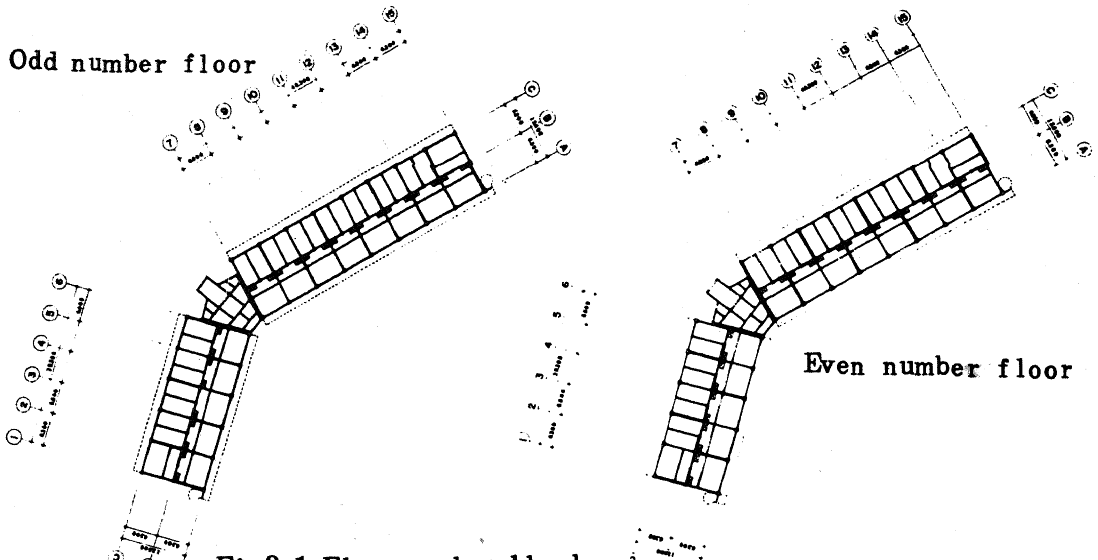


Fig3-1 Floor and wall plan

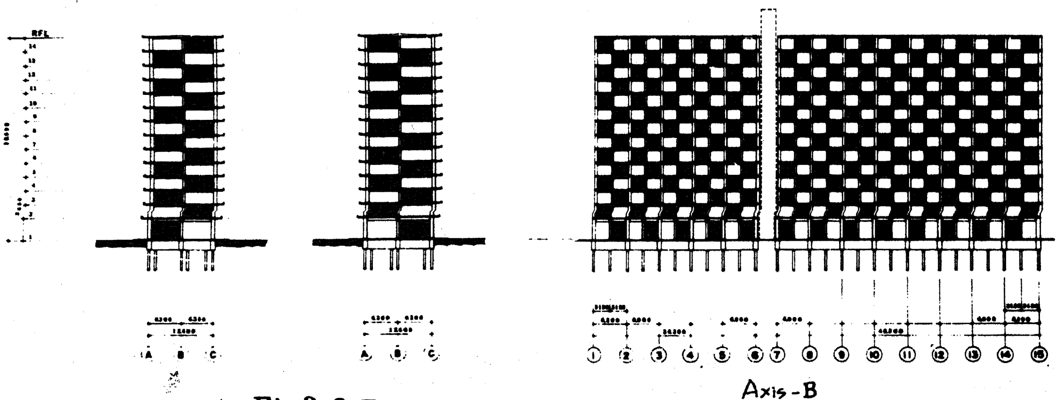
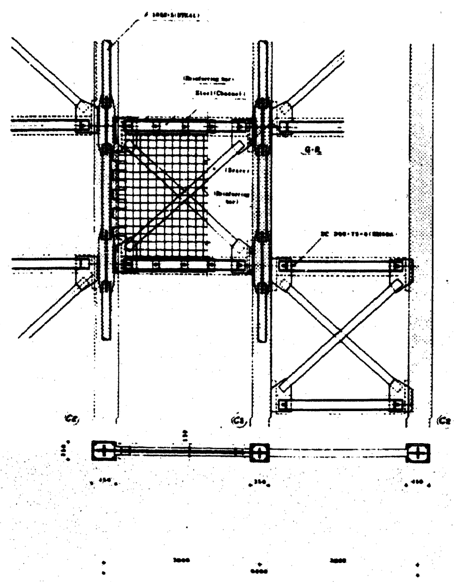


Fig3-2 Framing elevation



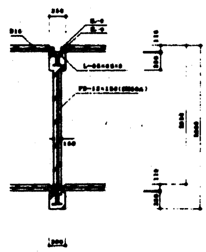


Fig3-3 Detail of unit shear wall

DISCUSSION

B.R. Seth (India)

The paper lacks the comparison with the one with full of same dimensions shear walls in both end bays, which involved the same quantity of materials. The discussor thinks that this arrangement will be more effective.

Kaveti Seetharamulu (India)

The authors are to be commended for suggesting a new form of shear wall, Fig. 1 (for 3-spans) which is an improved substitute to the conventional coupled shear wall, Fig. 2. The provision of shear walls while providing stiffness give rise to excessive base moments. It is a coincidence that the discussor (At IIT, Delhi) has been investigating a slightly modified form of checkered wall, Fig. 3(a). It is a substitute to coupled wall Fig. 2 but the material used is same as shown for the frame Fig. 3(b).

For the proposed assemblage the following are the advantages:

1. Reduced moment at the base (under lateral loads)
2. Reduced deflections as compared to Fig. 3(b) frame for moderately tall buildings.
3. Convenient size from handling considerations (Prefab)

Disadvantages,

1. Idealisation of line element cannot be used (Analysed by FEM)
2. Girders cannot be assumed to be inextensible due to large axial forces (compressions and tensions in girders of alternating levels)
3. Care while designing connections of skeletal members with the panel at its corners. The last aspect (joints) has been investigated by self and Mr. Prasad Rao (IIT, Delhi, India) using reinforced concrete models.

The discussor would like to have the comments on the proposed modified form.

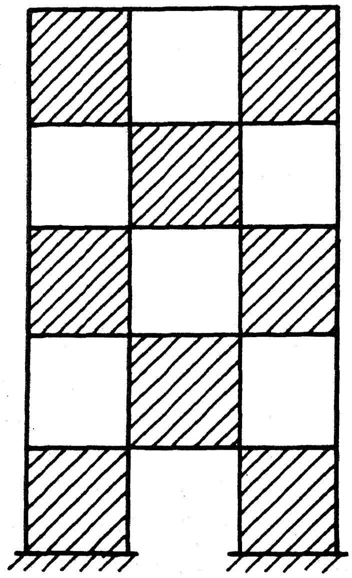


FIG. 1

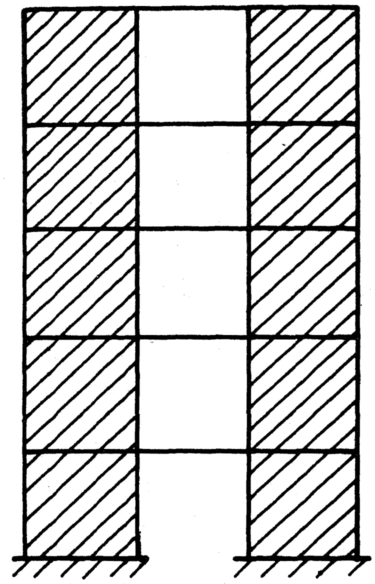
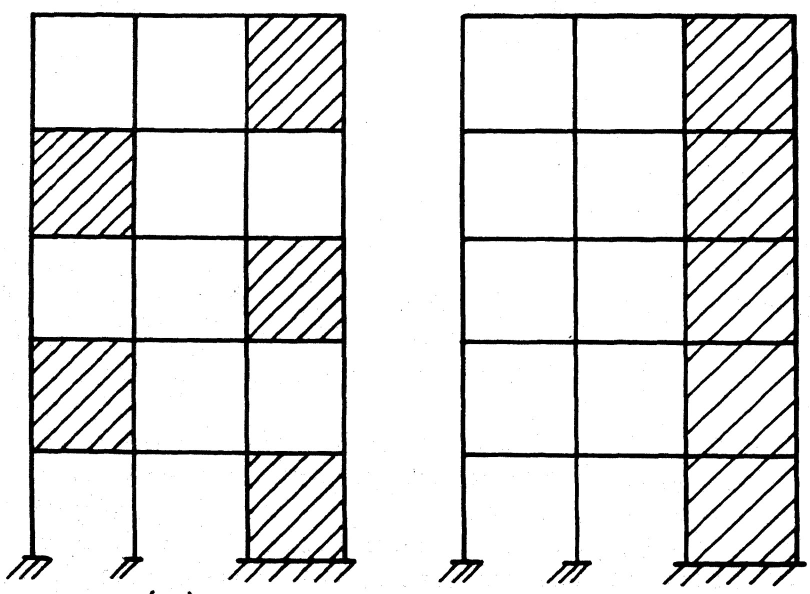


FIG. 2



(a) (b)

FIG. 3

Author's Closure

With regard to the question of Mr. Seetharamulu, we wish to state that his remarks were related to the comparison of the effect of a checkered shear wall type and a coupled shear wall type. We think the most effectural merit of using checkered shear wall frames is that sufficient strength against lateral forces without stress concentrations can be obtained.

On the other hand, in the coupled shear wall frames, concentrated stress will be produced at boundary beams. So, the maximum bearing strength depends on the yield strength of boundary beams.

To supplement the information in the enclosed paper, let us explain several points of our experimental study reported elsewhere.

a) Equivalent of five-storeyed and four-spanned buildings designed as 1/3 - to 1/4 - scale models. Both frames are built with the same quantity of materials.

b) Results of experiments on frame with coupled shear walls:

loads are resisted by each group of shear wall working separately and maximum bearing strength is equal to 310 tons.

c) Results of experiments on frame with checkered shear walls:

There is effective behaviour against lateral loads with all of the shear walls working together and maximum bearing strength is equal to 460 tons.

d) The maximum bearing strength of the checkered wall structure is 88 kg/cm^2 in term of mean shear stress of wall, approximately 1.5 times the 60 kg/cm^2 for the coupled shear wall structure.