RAFT-REINFORCED CONCRETE SKELETON BUILDINGS SUBJECTED TO SETTLEMENT AND/OR TILT

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الملخص

التداخل في السلوك مابين الهيكل الخرساني لمبنى واللبشة الخرسانية وحوائط الطوب والتربة والمنشآت المجاورة بالإضافة إلى عملية إنشاء المبنى معقد جدا. في هذه البحث تمت دارسة مشكلة الهبوط الغير متساوي وميل المباني لمنشآت خرسانية على لبشة مسلحة مع وجود حوائط من الطوب باستخدام العناصر المحددة (عناصر: كمرة، لوح، زنبرك) حيث قدم المؤلف دراسة لمبنى في بورسعيد بمصر من تجربته الشخصية في الاستشارات الهندسية. المبنى مؤسس على قطاع تربة معرض للهبوط عرضة أقل من ارتفاعه. تم دراسة تأثير وجود حوائط القص الخرسانية في الأدوار الأولى من المبنى. تم تمثيل الحائط الجانبي للمبنى بما يشمل الأعمدة والكمرات تمثيلاً في مستوي رأسي بطريقة العناصر المحددة. كما تم تمديد الدراسة إلى مبنى عرضة يساوى ارتفاعه تقريبا بالإضافة إلي دراسة تأثير شكل تشكل اللبشة وسمك اللبشة على الإجهادات والقوى في الحوائط والأعمدة، الكمرات واللبشة. توصل البحث إلي توصيات على أساس هذه الدراسة لتقدير أبعاد الهيكل الإنشائي والمسافة بين المباني وطريقة تقدير الأضرار الناتجة من هبوط المباني.

ABSTRACT

Interaction between R.C skeleton-raft-brick walls-soil-adjacent structures and/or construction is very complicated. In this study the author studied the problem of differential settlement and tilting for R.C skeleton-raft-brick walls buildings using finite element (beam, plate, and spring elements). The author presented a case study for tilting of a building with small width from his consulting experience in port-said Egypt in which soil profile is susceptible to settlement. The building sidewall including beams and columns is represented by 2-D finite element analysis. The research includes a study for influence of existence of R.C shear wall on skeleton response of the study case building. The research was expanded to study buildings with width approximately equal to height. Influence of deflected shape of raft and raft thickness on stress and forces in walls, columns, beams, and raft were studied. Recommendations based on this study for building skeleton dimensions, building spacing, and method of assessing building damage due to settlement were given.

KEYWORDS: Differential settlement; Tilt; Raft; Brick walls; Shear walls; Bending stresses; Shear stresses; Beam; Column; Finite element.

INTRODUCTION

With large growth of population and increase in land price, buildings constructed higher. Differential settlement stills a problem for old and new building especially in crowded closed building cities. Although settlement problems has been studied from long time, but the interaction between building skeleton, soil, and/or adjacent structure, and/or adjacent construction, and building construction sequence is very complicated. Each building is a unique case has to be studied separately science any change in one parameter will influence the building response. In this study a literature review for damage to buildings due to differential settlement is presented. A case study for 11 story tilted building in Port-Said Egypt is analyzed with existence of shear wall and without shear wall. A parametric study is presented using the same number of stories, columns dimensions and spacing. Finite element analysis is performed using STAAD program. Shear and brick walls are represented by plate element plane stress. Beams and columns are represented by beam element. Soil is represented by springs. Tables (5 and 6) show all the cases properties analyzed in this study. Conclusions are presented based on the results of this study.

DAMAGE TO BUILDINGS DUE TO DIFFERENTIAL SETTLEMENT

Tables (1, 2, 3, and 4) show different criteria for evaluating damage to buildings due to differential settlement.

Table 1: Tolerable differential settlement of buildings, mm

Criterion	Isolated foundations	Rafts
Angular distortion (cracking)	1/300	
Greatest differential settlement		
Clays	45 (35)	
Sands	32 (25)	
Maximum settlement		
Clays	75	75-125 (65-100)
Sands	50	50-75(35-65)

MacDonald and Skempton [1] made a study of 98 buildings, bearing walls, steel, and reinforced concrete construction (Table 1). This study was confirmed by Grant et al. [2] from a study of 95 additional buildings. Feld [3] cited a rather large number of settled structures. Wahls [4] commented on Table (1):

The values in brackets are recommended for design; others are the range of settlements found for satisfactory structural performance. In assessing what constitutes an acceptable slope, one must carefully look at the differential movement between two adjacent pints. Construction materials that are more ductile-for example, steel-can tolerate larger movements than either concrete or load-bearing masonry walls. Long time spans settlement allows the structure to adjust and better resist differential movement.

Table 2: Angular distortion limits by Bjerrum [6]

1/150	Structural damage of general buildings expected
1/250	Tilting of high rigid buildings expected
1/300	Cracking in panel walls expected, Difficulties with overhead cranes.
1/500	Limit for buildings in which cracking is not permissible
1/600	Overstressing of structural frames with diagonals
1/750	Difficulties with machinery sensitive to settlement

In settlement calculations the ground surface is assumed free to move and no consideration for lateral movement, which eliminate the influence of the structure on ground deformation. Burd et-al [5] described a three-dimensional finite element modeling of tunneling-induced settlement of masonry buildings. Inclusion of structure with soil is called by Burd et al [5] coupled analysis. Burd et al [5] concluded that a lateral restraint provided by the ground reduces the extent of tensile stress in the building for sagging deformation.

Table 3: Values of acceptable slopes between two adjacent points from the U.S.S.R. building code are cited by Bowles [7]

Structure	On sand or hard clay	On plastic clay	Average max. Settlement, mm
Crane runway	0.003	0.003	
Steel and concrete frames	0.002	0.002	100
End rows of brick-clad frame	0.0007	0.001	150
Where strain does not occur	0.005	0.005	
Multistory brick wall			25 L/H $\geq$ 2.5
L/H to 3	0.0003	0.0004	100 L/H $\leq$ 1.5
Multistory brick wall L/H over 5	0.0005	0.0007	
One-story mill buildings	0.001	0.001	
Smokestacks, water towers, ring foundations	0.004	0.004	300

L = column spacing, δ = differential settlement, H = height of wall above foundation (from Mikhejev et al. [8] and Polshin and Tokar [9]). Differential settlement estimated to equal 0.75 δ_{max}

Structure	Max. δ /L
Masonry (centre sag)	1/250 – 1/700
(edge sag)	1/300 – 1/1000
Masonry and steel	1/500
Steel with metal siding	1/250
Tail structures	< 1/300 (so tilt not noticeable)
Storage tanks (centre-to-edge)	< 1/300

Table :4 Damage categories for masonry walls (Boscardin and Cording [10])

Maximum principal tensile strain %	**Expected severity of damage**
0 - 0.05	Negligible
0.05 - 0.15	Slight
0.15 - 0.3	Moderate
> 0.30	Severe

For buildings subjected to hogging, however, lateral ground restraint does not have this effect. Interaction analysis based on an elastic structure described by (Potts and Addenbrooke [11]) may be useful for building deforming in a sagging mode. Finite element analysis has been used in modeling different settlement problems for buildings, for example [12] to [25]. It is obvious that most of building problems arise from some lake of soil information and the intension of not spending money on soil investigation and study building protection. Building repairs to settlement damage may cause more money than initial careful study for building protection from damage due to settlement.

CASE STUDY

The author present a case study for building located in Port-Said Egypt. The building is reinforced concrete eleven stories with short width (11 m.) and 17 m. length. The building is subjected to settlement and tilt. Soil profile consists of: Top layer of fine to medium, gray to dark gray, SAND, with trace to some of broken marine shells (9 m thickness under raft footing). – Second layer of medium to soft silty, dark gray clay, with increase in over consolidation of clay with depth. The clay layer extends to a depth about 50 m. Figure (1) shows the location of building in case study and construction sequence with respect to surrounding buildings. Note the close distance between buildings (1 and 3), which are less than the thickness of sand under footings. The direction of building tilt is toward building (3). Tilt and settlement could be reduced much if; building height reduced, increase raft area, and/or increase spacing between buildings (1 and 4). Table (5) shows columns and beams dimensions on axis (1 and 2) for the case study and for all other cases in Table (6). Figure (2) show the finite element model with shear wall for one side of the building which is analyzed as a model for case study (1 and 2). Figure (3) same as Figure (2) but with columns instead of shear wall (case 3 and 4). Axis (1 and 2) are shown on Figure (1). Comment about the case study will be included in section titled analysis of case study.

Table 5: Columns dimensions

Cases 1 and 2								
	Ground level	Level 1 , 2	Level 3	Level 4	Level 5	Level 6	Level 7 , 8	Level 9 , 10
Axe (1)	25x80	25x80	25x70	25x60	25x60	25x60	25x50	25x30
Axe (2)	Shear wall 15 cm	Shear wall 15 cm	25x80	25x80	25x80	25x60	25x60	25x50
	Cases 3 ,4, 5, 6,7 and 8							
Axe (1)	25x80	25x80	25x70	25x70	25x60	25x60	25x50	25x30
Axe (2)	25x100	25x100	25x80	25x80	25x80	25x60	25x60	25x50

PARAMETRIC STUDY

Same characteristics of building used in case study is mentioned in Table (6) as case (1). The analysis extended to another 7 different cases included in Table (6).

Table 6: Description of cases studied

Case name	Case NO.	Existence of shear wall 3 levels	No. of spans	Existence of loads on columns	Raft thickness m	Coefficient of subgrade reaction Ks kN/m^3	Enforced deflection on left side Cm.	Enforced deflection on right side Cm.
Raft-wall	1	yes	3	No	1.0	2000	8	1.0
Raft-wall-load	2	yes	3	Yes	1.0	2000	8	1.0
Raft-frame	3	No	3	No	1.0	2000	8	1.0
Raft-frame-load	4	No	3	Yes	1.0	2000	8	1.0
Raft-frame-con	5	No	9	No	1.0	2000	8	1.0
Raft-frame-con-load0801	6	No	9	Yes	1.0	2000	8	1.0
Raft-frame-con-load	7	No	9	Yes	1.0	6500	8	--
Raft-frame-con-load40	8	No	9	Yes	0.4	6500	8	--

Figures (4,5,6,7,8, and 9) present the deformation shape for cases (1,2,3,4,5, and 6). Axises (1 and 2) are shown on Figure (8). All beams in all cases studied are 15 cm width x 60 cm depth. Shear walls are reinforced concrete (15 cm thick). All other walls are brick walls (15 cm thick). Figures (10 to 17) presented shear force in beams and columns for cases (1 to 8) observe the difference and see Table (7) for comparison. Figures (18 to 25) present the bending moments in beams and columns for cases (1 to 8) observe the difference and see Table (7) for comparison. Figures (26 to 31) present the shear stress in brick walls for the side of building analyzed for cases ((1 and 3), (2 and 4), 5, 6, 8, and 7) observe the difference and see Table (9) for comparison. The value of maximum (($\sigma_1 - \sigma_3$), σ_x, and σ_y) and their locations in brick walls are also presented in Table (9).

ANALYSIS OF RESULTS

It is observed that in all analysis the bending moment and shear developed in the first level column is very high if compared with moment and shear developed in upper levels, this is due to high rotation developed between columns and raft. It may be if the analysis is nonlinear incremental there will be redistribution to bending moment. The bending moment in raft for cases (1 to 7) is almost same. The analyses, which are presented, next based on the summary of results in Tables (7, 8, and 9).

Table 7: Behavior of R.c skeleton (Beam and Column)

Case No.	Max. rotation at col.-raft rad	Max horizontal movement Cm.	Max. moment in col. First level kN.m	Max. moment in col. second level kN.m	Max shear in first level col. kN	Max shear in col. Second level kN	Max moment in first level beam kN.m	Max moment in second level beam kN.m
1	0.0084	20.7	1096.2	165.48	403.88	54.06	155.56	55.57
2	0.00833	20.7	1054.31	157.29	390.75	44.92	130.11	45.66
3	0.0084	20.4	799.65	111.96	322.77	43.14	180.0	102.56
4	0.0083	20.4	852.41	112.41	307.77	37.8	180.11	103.86
5	0.0056	7.0	734.74	132.09	246.44	97.05	192.31	123.18
6	0.0074	6.6	1126.29	232.21	421.22	154.51	270.75	199.42
7	0.00415	4.9	689.5	130.29	257.32	73.27	162.77	132.92
8	0.0073	4.5	411.47	174.59	145.0	119.33	248.92	205.98

Table 8: Behavior of raft foundation

Case No.	Raft thickness m	Max. moment in x direction M_x kN.m	Max. Shear stress in x direction SQ_x kN/m^2	Max. rotation of raft rad
1	1.0	3696	1507.6	0.0084
2	1.0	3308	1245.0	0.00833
3	1.0	3717	1540	0.0084
4	1.0	3338.71	1249.33	0.0083
5	1.0	3606.44	1343.12	0.0056
6	1.0	3636.58	1227.0	0.0074
7	1.0	2799.34	1722.6	0.00415
8	0.40	395.8	2008	0.0073

Table 9: Behavior of brick walls

Case No.	Max. Shear stress τ_{xy}		Max. Principal stress difference $(\sigma_1 - \sigma_3)$		Max. Stress in x direction σ_x		Max. Stress in y direction σ_y	
	Value kN/m^2	Location (x,y)	Value kN/m^2	Location (x,y)	Value kN/m^2	Location (x,y)	Value kN/m^2	Location (x,y)
1	2656	5.5,1.5	11878	4.5, 0.5	1833	6.7,4.465	12295.5	4.3 , 0.5
2	4243	6.7, 9.135	18312.8	6.7, 4.46	2539.25	4.5,9.135	19342.2	6.7 , 0.5
3	1020.5	6.7, 9.135	2284.5	6.7, 9.135	629.76	6.7, 9.135	1656	6.7, 9.135
4	1335.1	6.7, 9.135	3766	6.7, 9.135	761.6	6.7, 9.135	3418	6.7, 9.135
5	230.17	5.5 , 3.5	460.32	5.5 , 3.5	127.6	0.5 , 1.5	196	1.5 , 0.5
6	235.59	27.5 , 3.5	501.3	5.5 , 3.5	239.14	26.3 , 11.93	288.7	31.5, 0.5
7	190.0	5.5 , 3.5	387.8	5.5 , 3.5	147.6	4.3 , 11.93	168.0	9.5 , 0.5
8	350.95	1.5 , 0.5	742.22	1.5 , 0.5	140.4	4.3 , 11.93	359.5	2.5 , 0.5

Case study

The actual building did not encounter any cracks in brick walls or reinforced concrete skeleton. The existence of shear wall and small width of the building make the building to be more rigid. The analysis cases (1 and 2) agree with what happened in the actual building with less stresses in all skeleton elements except the bending moment in first level because the author does not know exactly deformation shape at raft level. It seems that the actual behavior of the building is mostly tilt, which produces small deformation in skeleton elements.

Compare case (1) and case (3)

Existence of shear wall (case 1) causes the concentration of shear stresses in the zone of shear wall first few levels. Analysis of case (3) without existence of shear wall causes some shear stress distribution in brick walls in upper levels. Case (1) (building with shear wall) produces higher moment and shear in columns than case (3) (building without shear wall), but the moment in beams higher in first and second level for case (3) than for case (1).

Analysis with or without column load

In cases 1 to 4 (short width to height building) the change in bending and shear in columns and beams due to inclusion of column load are small. Comparisons between cases (5 and 6) (width=height buildings) show the increase in bending and shear in columns and beams are observable. The influence of existence of load on columns is obvious in cases (5 and 6) which are reflected in the difference in the value of raft rotation as shown in Figure (33).

Compare case (4) and case (6)

The increase in building width (case 6) causes increase in all stresses in columns and beams in first and second level compare with case (4). This is due to response of building more flexible in case (6) than in case (4).

Compare case (6) and case (7)

As expected for soil with higher stiffness (coefficient of subgrade reaction) the stresses in columns and beams in first and second levels are reduced.

Compare case (7) and case (8)

The reduction in raft thickness (case 8) causes reduction in bending moment, and shear in first level columns, also causes increase moments in first and second level beams and increase in moment in second level column. Case (8) produces τ_{xy} and (σ_1-σ_3) in brick walls with higher values than thicker raft in case (7).

Behavior of brick walls

In cases (1 and 2) the maximum shear stress located within the shear wall. Cases (3 and 4) (without shear wall) produces less shear stress τ_{xy}, but the value of (σ_1- σ_3) is higher than case (1). The location of maximum τ_{xy} and (σ_1- σ_3) are much higher in level for case (3) than for case (1).

RAFT-SOIL SETTLEMENT PROFILE

The key for estimation of location of cracks in buildings is predicting the rotation of structure elements, specially the deformed shape of raft. It is recommended when design buildings on soil profile susceptible to settlement to test the skeleton for different deformation expectable shapes. Figure (32) shows different expected raft deformation and the crack location. The cracks will happen at the location of maximum rotation. Figure (32) may be used in predicting the location of cracks in old or new building by estimating the raft deformation shape and the location of maximum settlement. Figure (33) presents a summary for the values of raft rotation under the eight models studied. Table (8) presents the maximum moment, shear, and rotation in raft.

CONCLUSIONS

The case study behavior in the field is well simulated in case (1 and 2). The existence of shear wall and short width of building governs the building behavior to tilt movement mostly, which explains the no damage happened in the building. If there is a small space between buildings caution should be considered in choosing the allowable stress under raft to reduce the possibility of differential settlement and tilt. Reduction in raft thickness increases stresses in beams in first and second level, thus for repair of buildings with thin raft the depth and reinforcement of beams in first and second levels should be increased. Buildings with large width respond more flexibly to differential settlement (in direction of building width) than building with small width. Estimation of possible deformation of building as shown in figure (32) will help in estimation of possibility of building damage.

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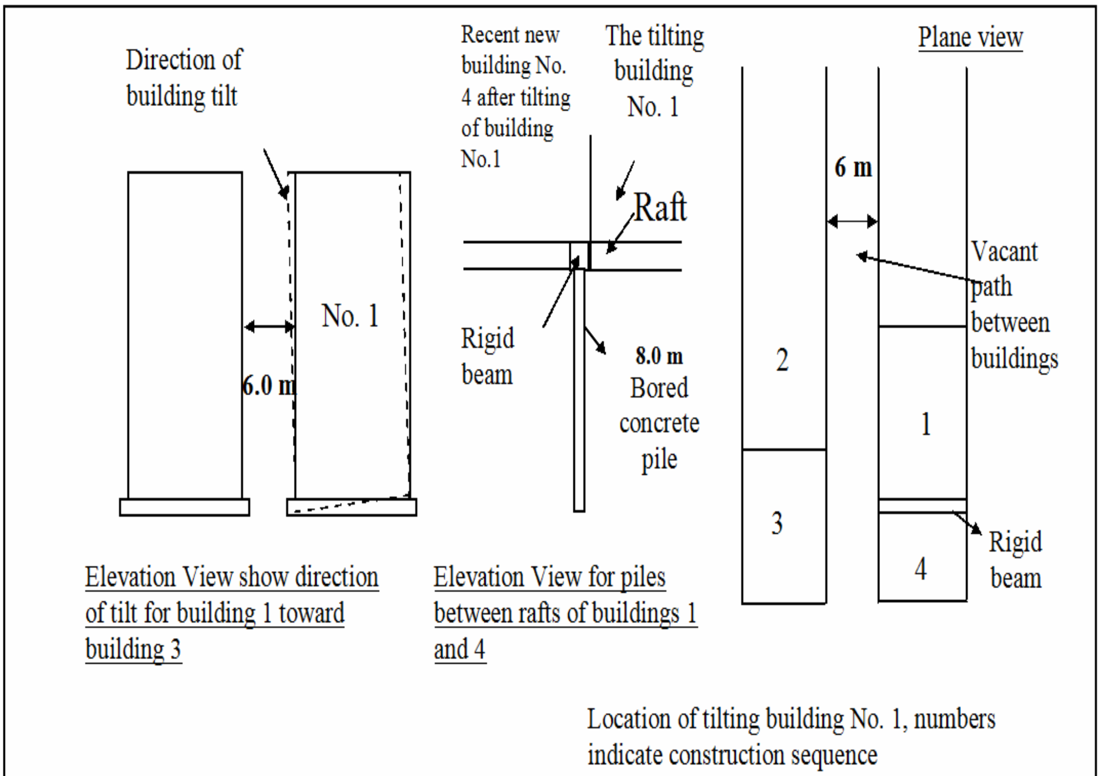


Figure 1: Location and characteristics of case study building

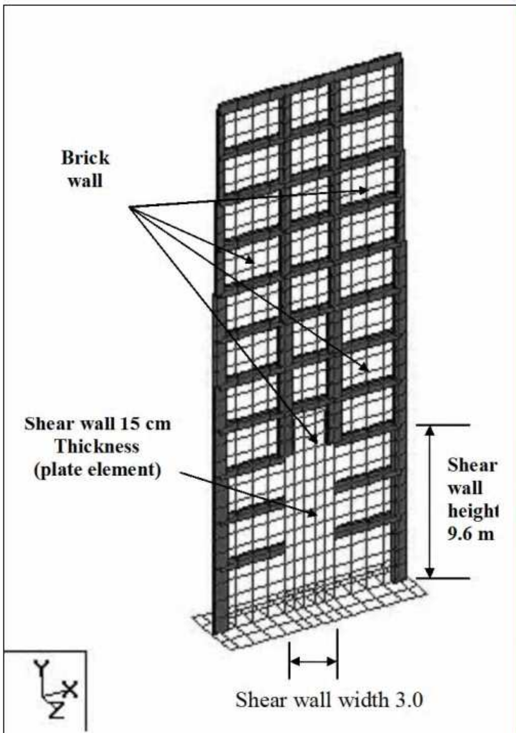


Figure 2: Finite element with shear wall Case (1 and 2)

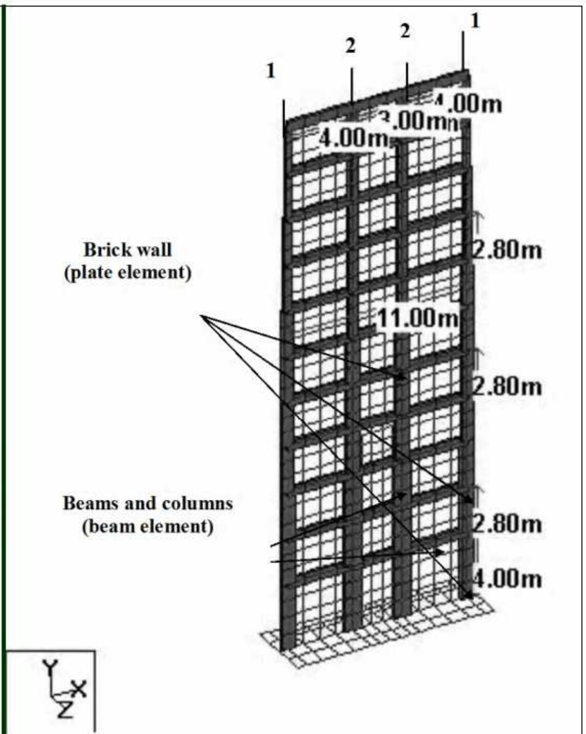
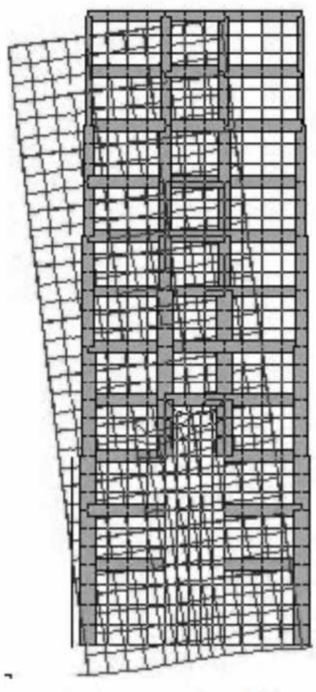


Figure 3: Finite element without shear Wall case (3 and 4)



Deformation Scale 0.05 m : 1.0 m on drawing

Figure 4: Deformed shape case (1)

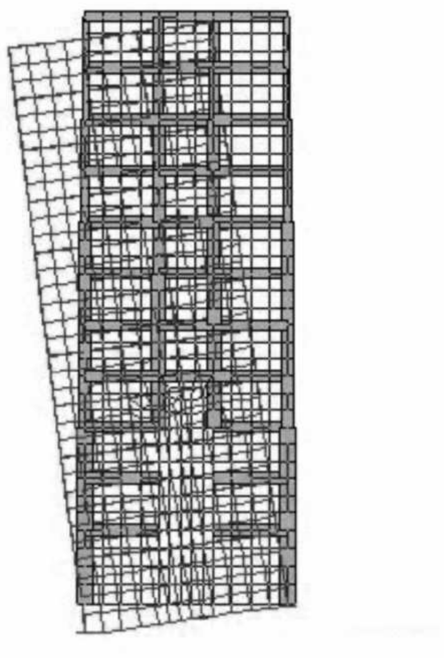


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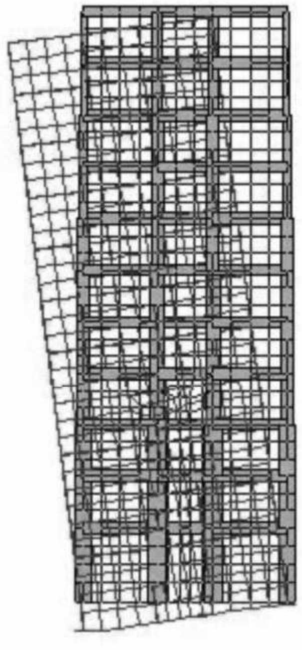
Figure 5: Deformed shape case (2)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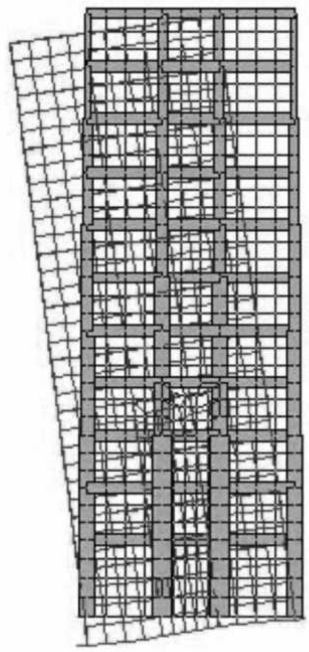
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Figure 6: Deformed shape case (3) **Figure 7: Deformed shape case (4)**

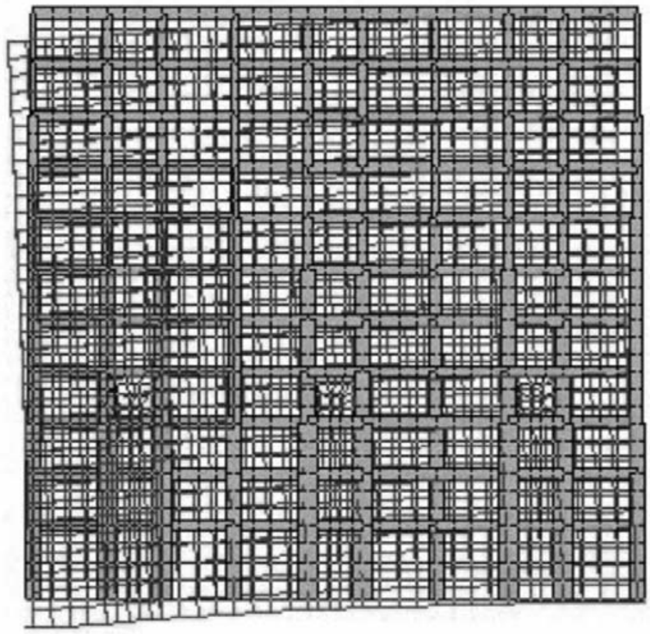

Deformation Scale 0.05 m : 1.0 m on drawing

Figure 8: Deformed shape case (5)

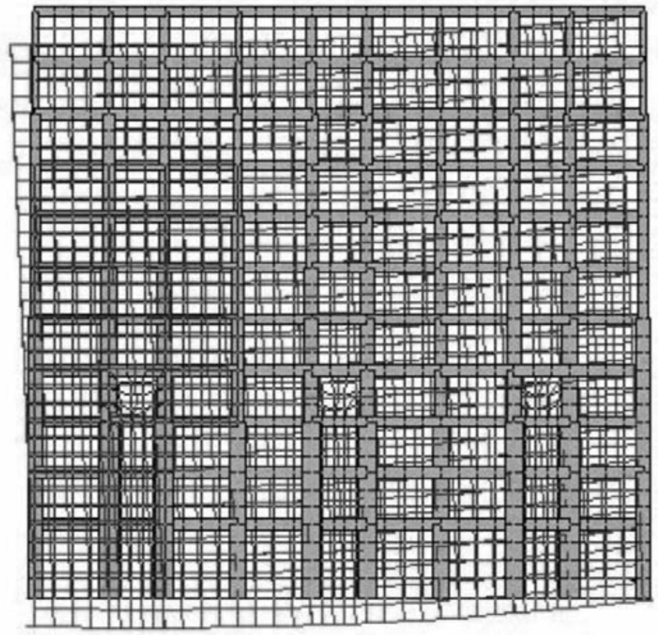


Figure 9: Deformed shape case (6)

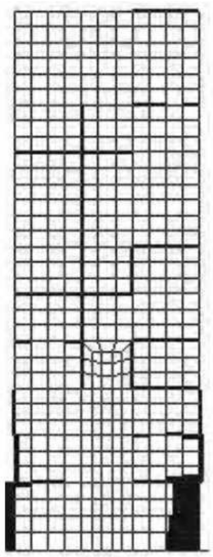


Figure 10: Shear force in beams and columns case (1)

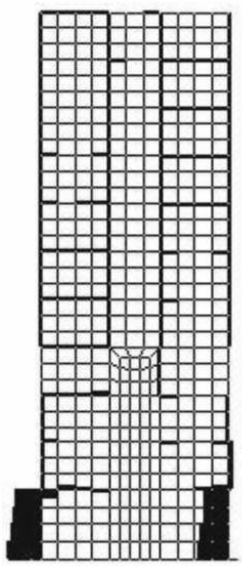
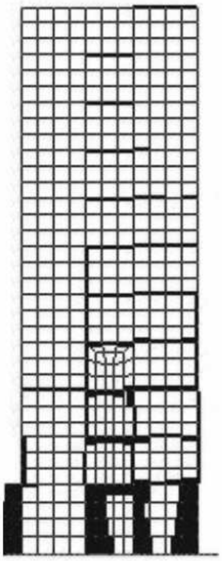
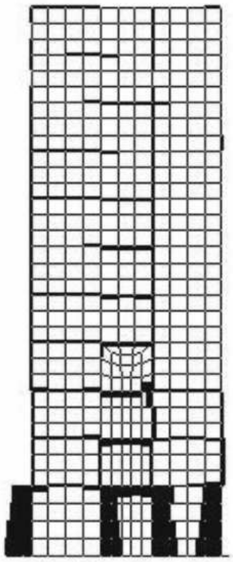


Figure 11: Shear force in beams and columns case (2)



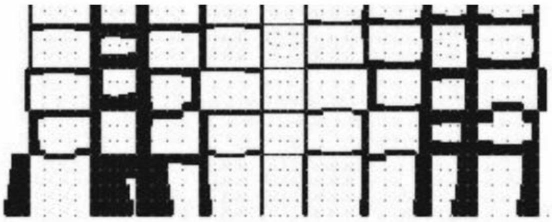
cale 200 kN : 1.0 m.

Figure 12: Shear force in beams and columns case (3)



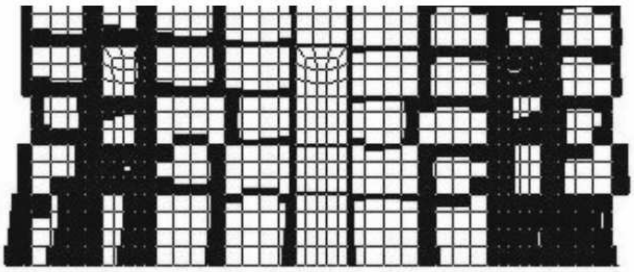
Scale 200 kN : 1.0 m.

Figure 13: Shear force in beams and columns case (4)



Scale 100 kN : 1.0 m.

Figure 14: Shear force in beams and columns for first four levels case (5)



Scale 100 kN : 1.0 m

Figure 15: Shear force in beams and columns for first four levels case (6)

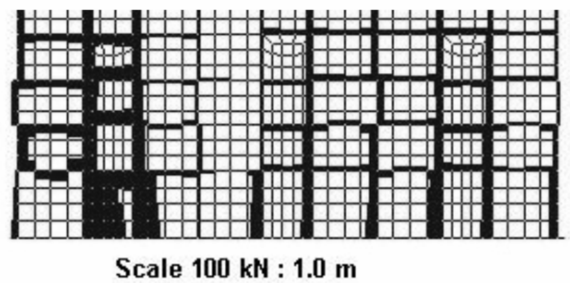


Figure 16: Shear force in beams and columns for first four levels case (7)

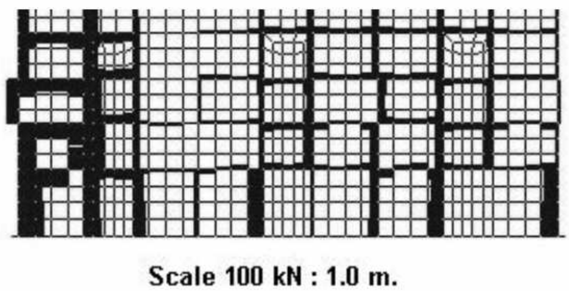


Figure 17: Shear force in beams and columns for first four levels case (8)

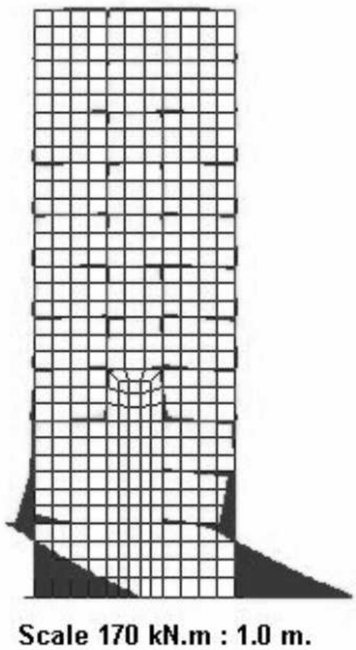


Figure 18: Bending moment of beams and columns case (1)

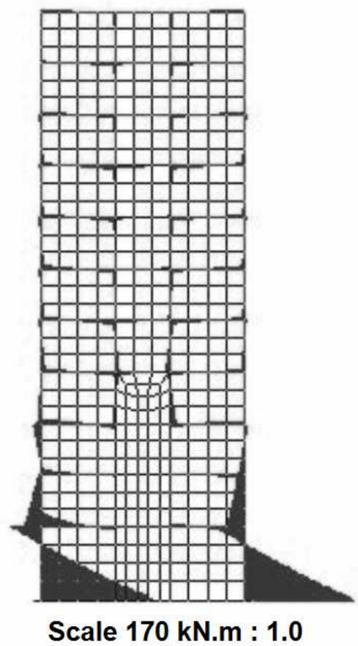


Figure 19: Bending moment of beams and columns case (2)

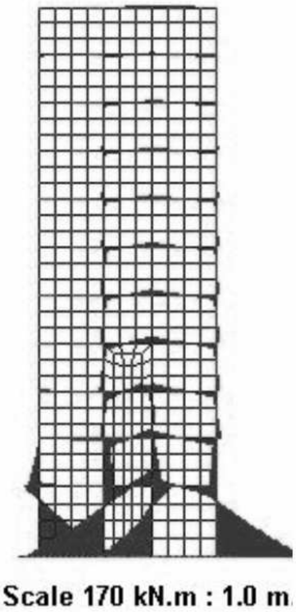


Figure 20: Bending moment of beams and columns case (3)

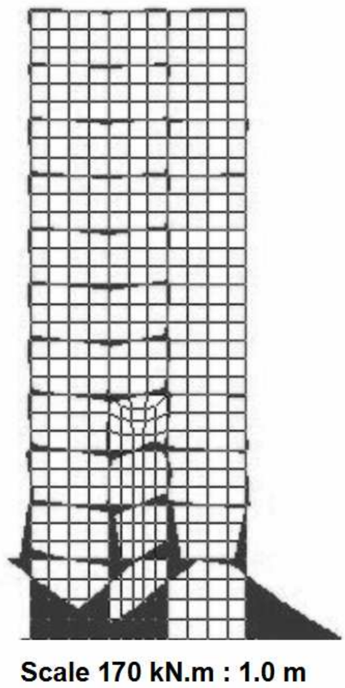


Figure 21: Bending moment of beams and columns case (4)

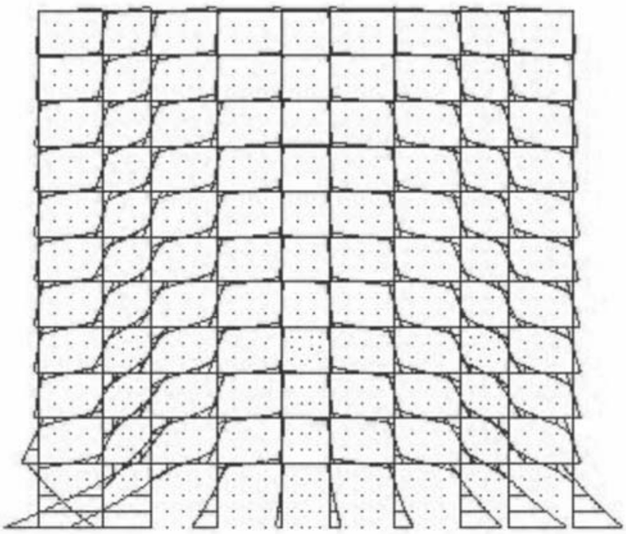
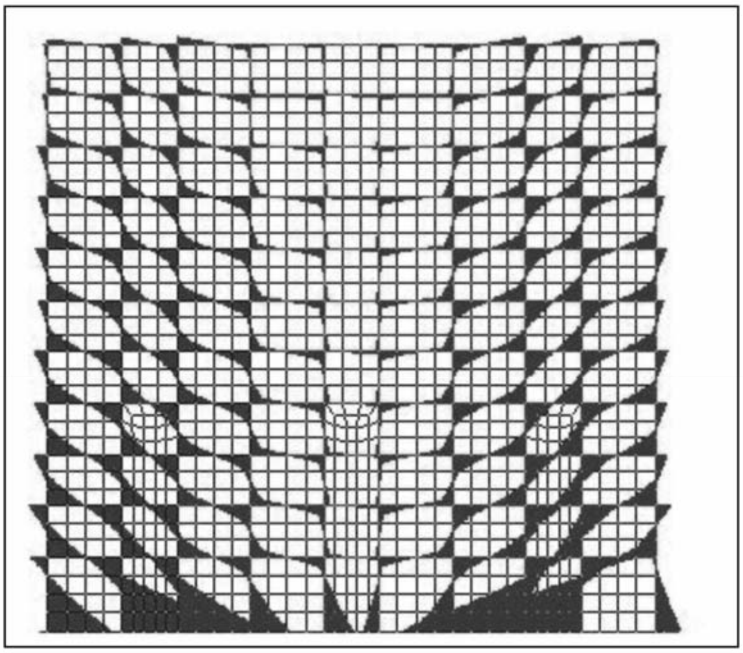
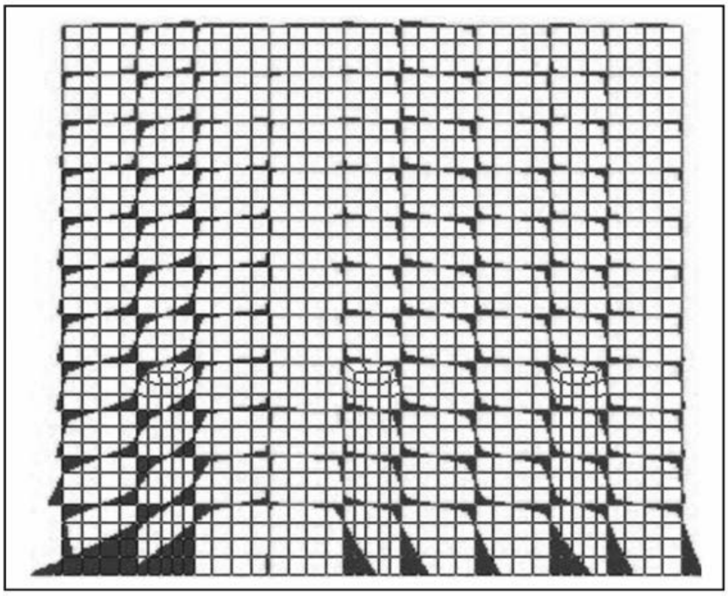


Figure 22: Bending moment of beams and columns case (5)



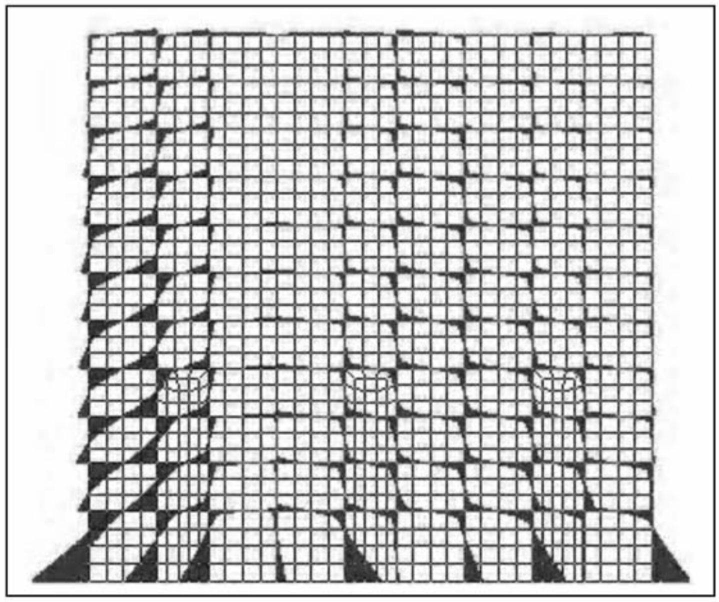
Scale 120 kN.m : 1.0 m

Figure 23: Bending moment of beams and columns case (6)



Scale 120 kN.m : 1.0 m

Figure 24: Bending moment of beams and columns case (7)



Scale 120 kN.m : 1.0 m

Figure 25: Bending moment of beams and columns case (8)

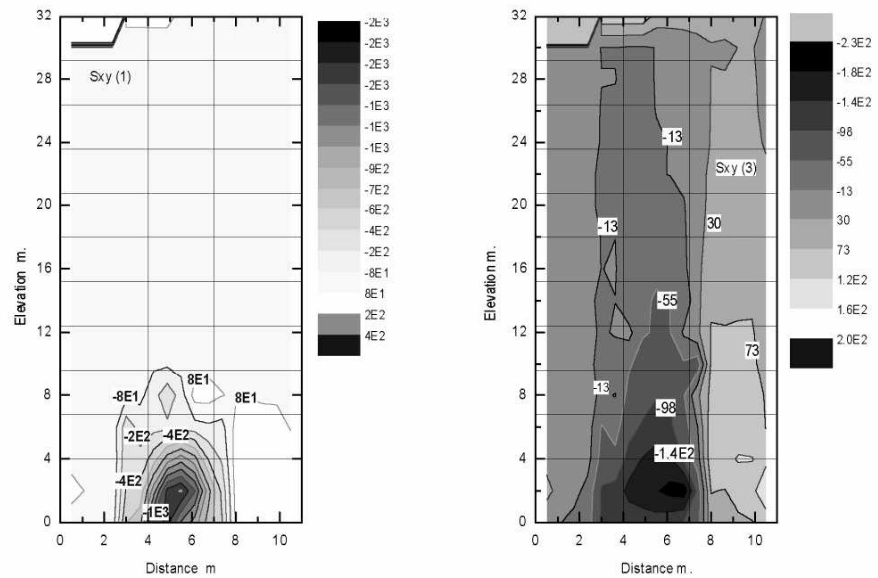


Figure 26: Shear stress in brick wall case (1) and case (3)

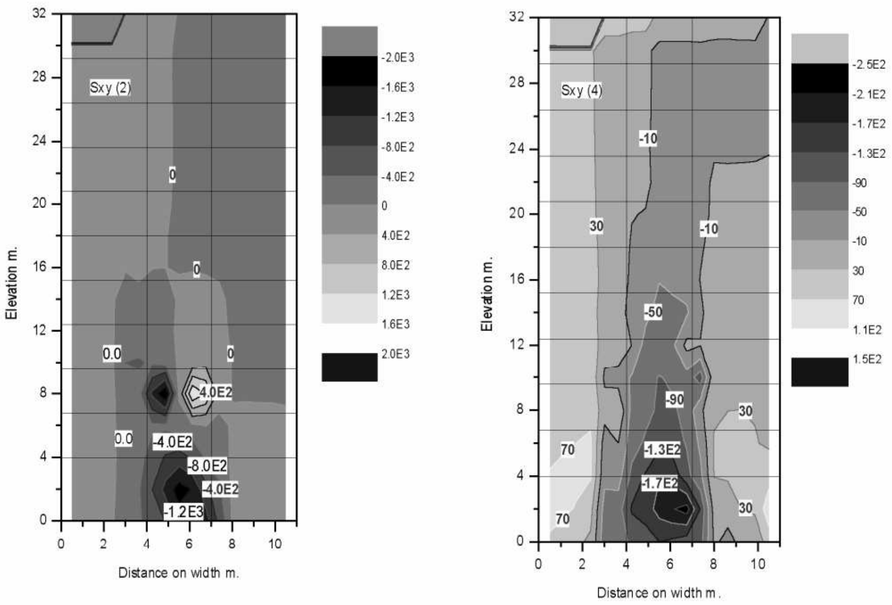


Figure 27: shear stress in brick wall case (2) and case (4)

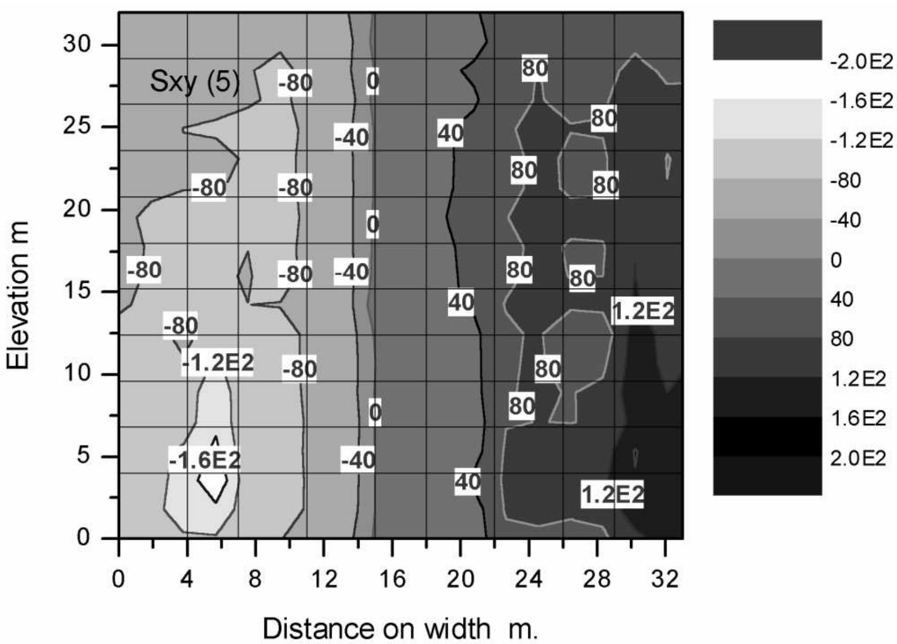


Figure 28: Shear stress in brick walls case (5)

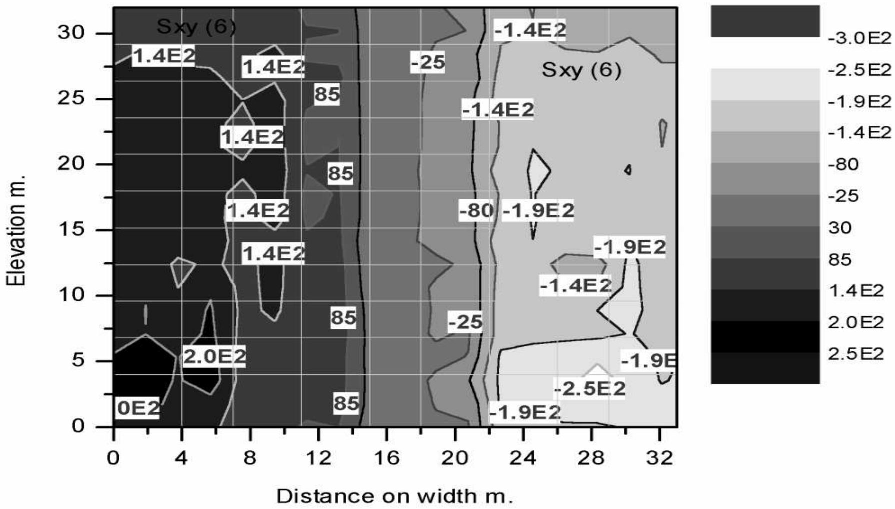


Figure 29: Shear stress in brick walls case (6)

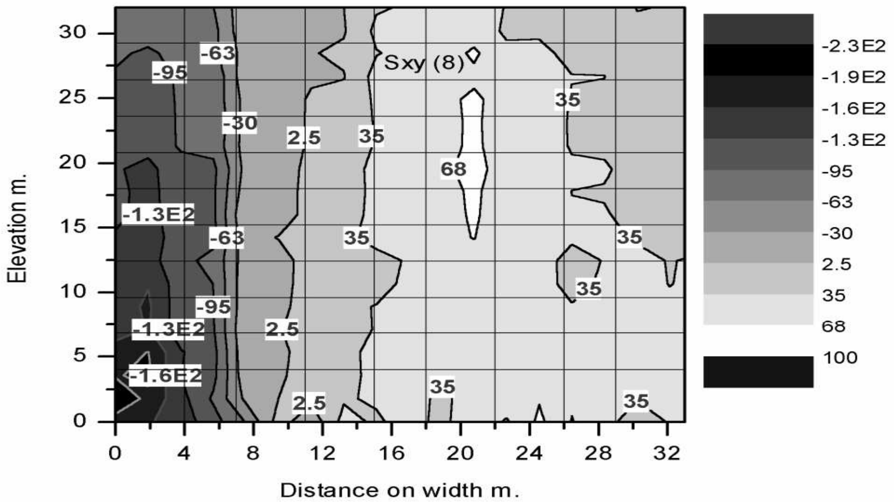


Figure 30: Shear stress in brick walls case (8)

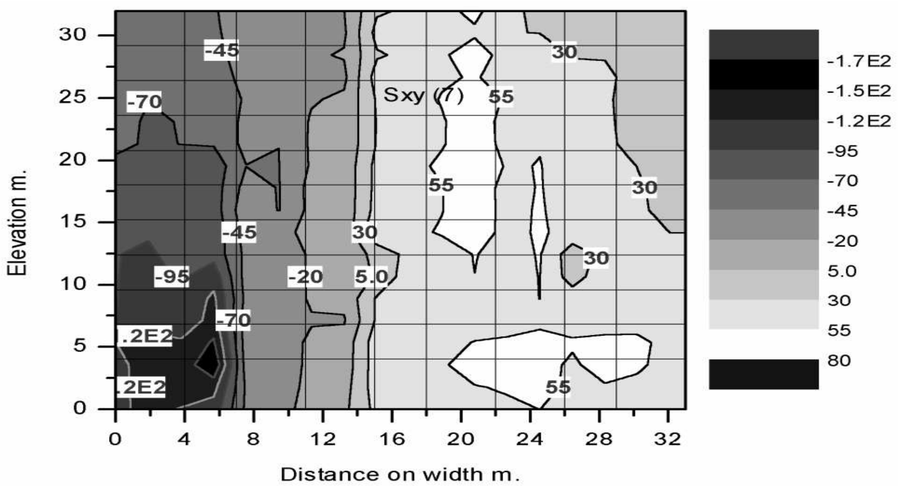


Figure 31: Shear stress in brick walls case (7)

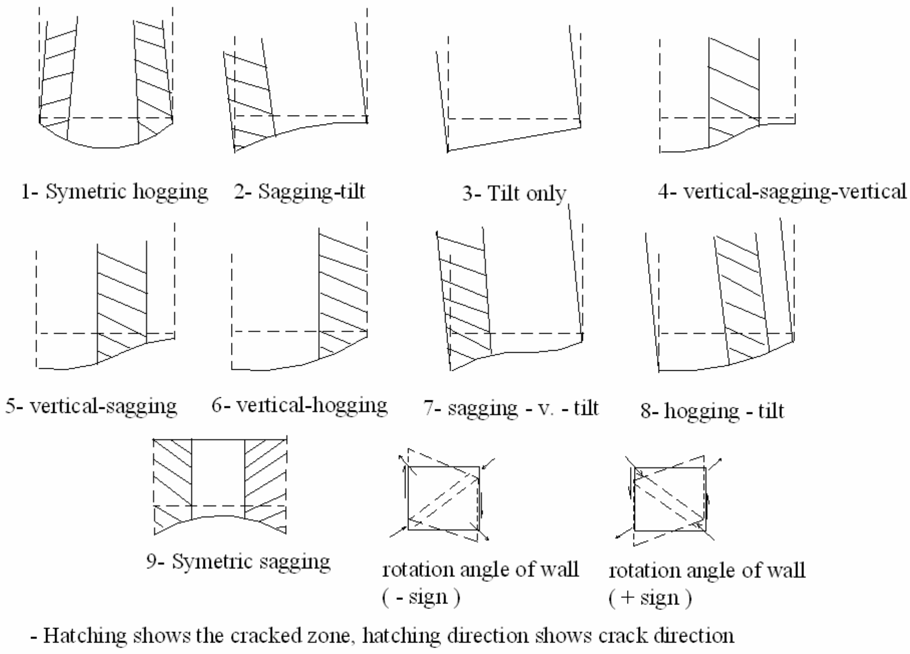


Figure 32 : Expected nine different cases for raft deformation and location of cracks

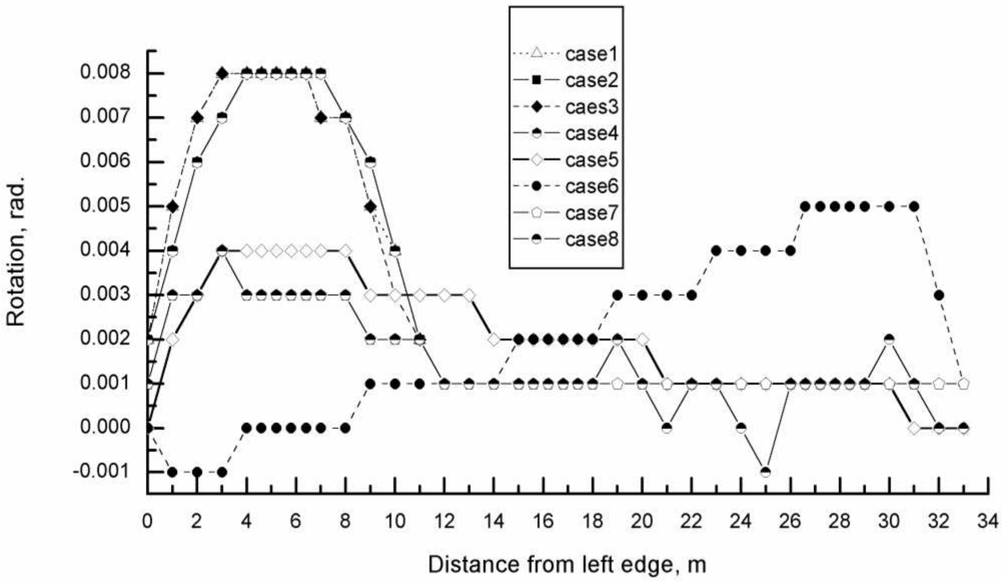


Figure 33: Rotation along raft for the eight cases studied