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Behaviour of 3D RC frames placed at different angles on shaking table

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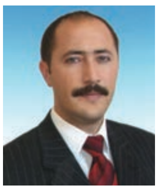

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Scientific Paper – Preliminary report

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Behaviour of 3D RC frames placed at different angles on shaking table

Behaviour of RC frames placed at different angles (biaxially) on the shaking table is analysed in the paper. The testing was conducted on four two-storey one-bay 3D RC frames scaled down to 1:6 of the original size, the aim being to analyse defects commonly observed on residential buildings. All specimens had infill walls and similar window openings. The specimens were subjected to sinusoidal dynamic testing. Test results show that different failure modes occurred at all specimens in the X and Y directions.

Key words:
reinforced-concrete frame, shaking table, dynamic testing, failure mode

Prethodno priopćenje

Fatih Bahadir, Fatih Süleyman Balik

Ponašanje prostornih ab okvira postavljenih pod raznim kutovima na potresni stol

U radu se analizira ponašanje ab okvira postavljenih pod raznim kutovima (dvoosno) na potresni stol. Ispitivanja su provedena na četiri dvokatna jednokrilna trodimenzionalna ab okvira izvedenih u mjerilu 1:6, a s ciljem analiziranja nedostataka koji se često uočavaju na stambenim građevinama. Svi uzorci imaju obodne zidove i jednake prozorske otvore. Na postavljenim uzorcima provedeno je sinusoidno dinamičko ispitivanje. Rezultati dobiveni u toku eksperimenta pokazali su da se kod svih uzoraka popuštanje razlikuje u smjerovima x i y.

Ključne riječi:
armiranobetonski ovir, potresni stol, dinamičko ispitivanje, oblik popuštanja

Vorherige Mitteilung

Fatih Bahadir, Fatih Süleyman Balik

Verhalten von räumlichen Stahlbetonrahmen, die unter verschiedenen Winkeln auf den Erdbebentisch aufgestellt werden

In der Abhandlung wird das Verhalten von Stahlbetonrahmen analysiert, die unter verschiedenen Winkeln (zweiachsig) auf den Erdbebentisch aufgestellt werden. Die Untersuchungen wurden auf vier zweistöckigen einflügligen dreidimensionalen Stahlbetonrahmen durchgeführt, die in einem Maßstab von 1:6 ausgeführt sind, mit dem Ziel die Mängel zu analysieren, die häufig bei Wohngebäuden bemerkt werden. Alle Modelle haben Umfassungswände und gleiche Fensteröffnungen. Bei den aufgestellten Modellen wurde eine sinusförmige dynamische Untersuchung durchgeführt. Die während des Experiments erhaltenen Ergebnisse zeigten, dass sich bei allen Modellen die Abspannung in den Richtungen x und y unterscheidet.

Schlüsselwörter:
Stahlbetonrahmen, Erdbebentisch, dynamische Untersuchung, Form der Abspannung

1. Introduction

Earthquakes are natural events that prevent realisation of development goals. The next earthquake event may happen today, in a week or in a few months, or in years or decades from now [1]. The laboratory testing related to earthquake resistance of buildings, aimed at simulating earthquake loads, is usually conducted using semi-dynamic or static tests. Details such as nonlinear behaviour of a structure under cyclic loading, plastic rotation capacity of members, shear capacity of column-beam joints, P-Δ effect, and damping ratio, are important in the review of a reinforced concrete structure. However, since earthquake loads are dynamic, static tests do not reflect real behaviour of the structures. Furthermore, since static tests are conducted step by step, the loads applied to the structure cannot accurately reflect the inertia effect on the building. Shaking tables are therefore preferred in this type of laboratory testing.

In the shaking table experiments, the most important detail is the scaling of specimens. With regard to test specimens and experimental techniques, different scaling rules are proposed by Harris and Sabnis [2] for experiments and materials. For educational purposes, models with scale factor 1:10 or less [3-7] are being used in construction laboratories for shake table testing. There we can observe different modes in the building, while we can observe damage types in buildings in case of models with a scale factor greater than 1:10 [8-10]. However, the shaking table experiments with samples scaled at 1:1, 1:2 and 1:3 are both expensive and large as a system [11-14]. If specimens of these scales are prepared for shaking table, the cost and time of experimental studies are quite high. For these reasons, test specimens were produced at the 1:6 geometric scale, and test specimens were tested at a low-cost shaking table. Since 1960, shaking tables have been used for scientific research on earthquakes and in structural engineering studies [15, 16]. From the past to present, structural mechanics laboratories of many countries have manufactured, developed and used shaking tables for experimental studies at 1:1 or other scales [9, 17, 18].

The location and duration of earthquakes can not be predicted [1]. Therefore, buildings may be affected by earthquake loads in different directions. That is why, in this study, test specimens were placed biaxially on the shaking table and subjected to dynamic testing. It is expected that the damage types and failure modes that occur during earthquakes will also occur on these specimens. The expected damage types and failure modes are the torsion effect, short column behaviour, soft storeys, and shear-flexural cracks on structural members and brick walls.

For these reasons, in this experimental study, reinforced concrete 3D frames forming two storeys with one bay, realized at the 1:6 geometric scale, were placed at different angles (biaxial) on a low-cost shaking table. The process included construction of four specimens, placing these specimens at various angles (0, 30, 45 and 60 degrees) on the shaking table, and sinusoidal dynamic testing.

2. Materials and Methods

2.1. Description of test specimens

In this experimental study, four RC frames were used to produce two 3D storeys on the geometric scale of 1:6. The frames, containing deficiencies commonly observed in residential buildings in Turkey, were subjected to biaxial testing on the shaking table. All specimens contained brick walls and the same window openings. The experiments were prepared and conducted in the Structural Testing Laboratory of the Necmettin Erbakan University in Konya, Turkey (Figure 1).

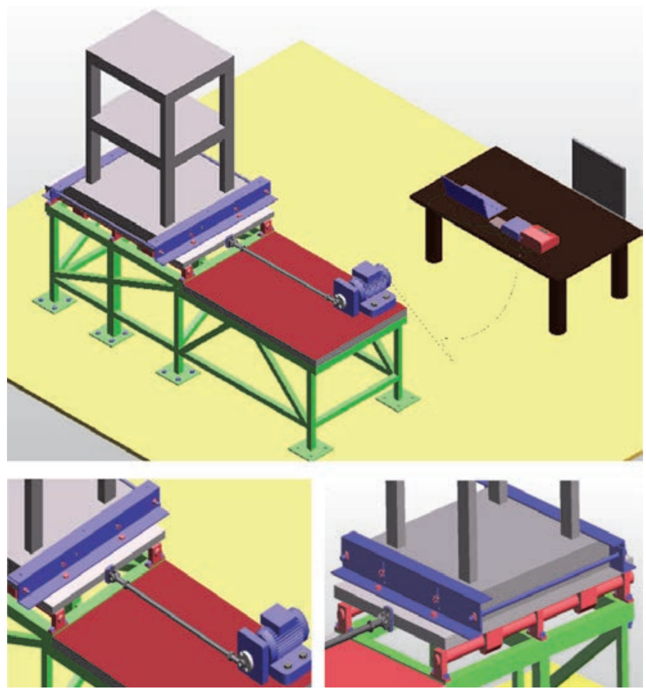


Figure 1. General diagram of test setup for experimental study

In four test specimens, the same values were used for the width and height of structural elements, concrete qualities and reinforcement forms of the frames (Figure 2). Test frames were deliberately detailed and constructed with some deficiencies such as low strength concrete, strong beam-weak column formation, wide spacing of beam and column stirrups, no column stirrups at the beam–column joints, and no confinement zones at the end of the columns and beams [19-21]. In addition to these deficiencies, the stirrups were prepared with hooks placed at 90° at free ends of columns and beams of the test specimens [19-21].

The height of one storey was 500 mm (3000 mm at real-size 1:1 scale). The length of the frame was 700 mm from one column to another. Plain bars were used for longitudinal reinforcement and stirrups. The column dimensions were 50x80 mm, and four 3 mm diameter bars were used as longitudinal reinforcement. The beam dimensions were 50 x 90 mm, and six 3 mm diameter plain bars were used. Reinforcing bars 2 mm in width, spaced at 50 mm intervals, were used as stirrups at columns and beams of specimens. Dimensional and reinforcement details of the specimens are shown in Figure 2 [22].

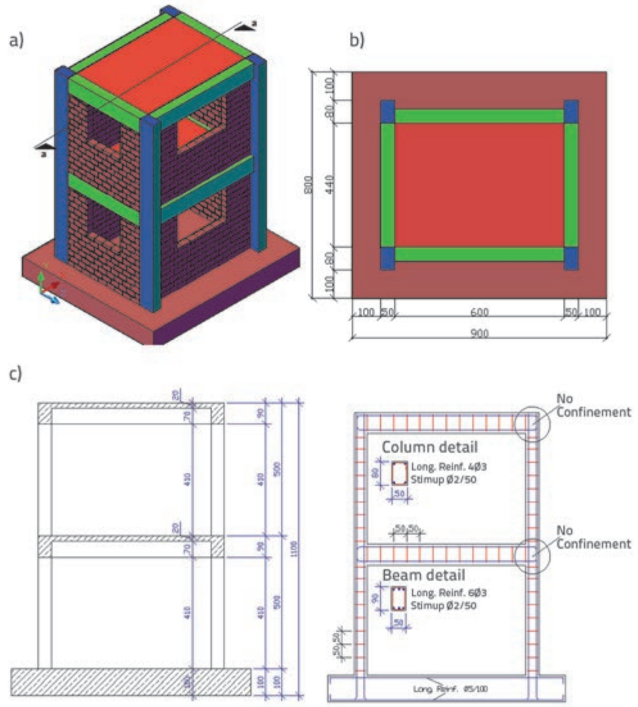


Figure 2. Dimensional and reinforcement details of general specimen (dimensions in mm)

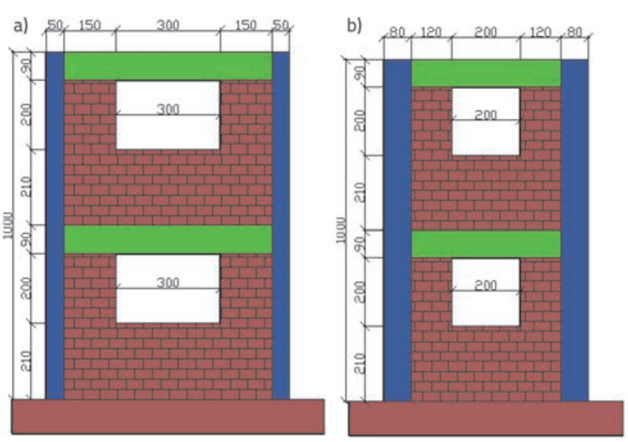


Figure 3. Dimensions of window openings (dimensions in mm)

All specimens were equipped with 200/300 mm window openings at mid-span on two long faces, and 200/200 mm window openings at mid-span on two short faces (Figure 3). Brick walls were produced to represent an external frame of the real structure. The middle axis of the brick walls and frame did not coincide; rather external surface of the brick wall was at the same axis as the external surface of the beams. The thickness of the wall was 30 mm, while the depth of the columns was 50 mm or 80 mm. The bricks used in the infill walls were made by cutting gas concrete. The brick dimensions were 30x50x25 mm [22].

Reinforcement was produced for columns and beams and placed in the steel formwork. The concrete for specimens was poured vertically into formworks. The second-storey concrete was cast seven days after the first-storey concrete casting [23]. The formwork was removed after the second-storey concrete casting. Sample production stages are shown in Figure 4.

Table 1. Scale factors for experimental study on shaking tables [2,18]

Parameter		Dimension	Scale factors
Loading	Force, *Q*	F	S_l^2
	Pressure, *q*	FL^{-2}	1
	Acceleration, *a*	LT^{-2}	1
	Gravitational acceleration, *g*	LT^{-2}	1
	Velocity, *v*	LT^{-1}	$S_l^{1/2}$
	Time, *t*	T	$S_l^{1/2}$
Loading	Linear dimension, *l*	L	S_l
	Displacement, δ	L	S_l
	Frequency, ω	T^{-1}	$S_l^{-1/2}$
	Area, A	L^2	S_l^2
	Volume, V	L^3	S_l^3
	Moment of inertia, I	L^4	S_l^4
Material properties	Modulus, E	FL^{-2}	1
	Stress, σ	FL^{-2}	1
	Strain, ε	-	1
	Poisson's ratio, ν	-	1
	Energy, EN	FL	S_l^3
	Mass density, ρ	$FL^{-4}T^2$	$1/S_l$

Figure 4. Sample production stages

Scale factors used for measurements and dimensions of specimens on the shake table are given in Table 1. According to the scale laws obtained from Table 1, the same ground motion was applied to specimens in short time periods and at high frequencies [18].

2.2. Material parameters

Specimen frames were cast with a low compressive strength concrete, as all test specimens were produced at 1:6 geometric scales. The maximum aggregate size of concrete was 3 mm. The aggregate grading used in concrete is shown in Figure 5. Geometric properties of aggregate were specified as per TS 3530 EN 933-1:2012 [24].

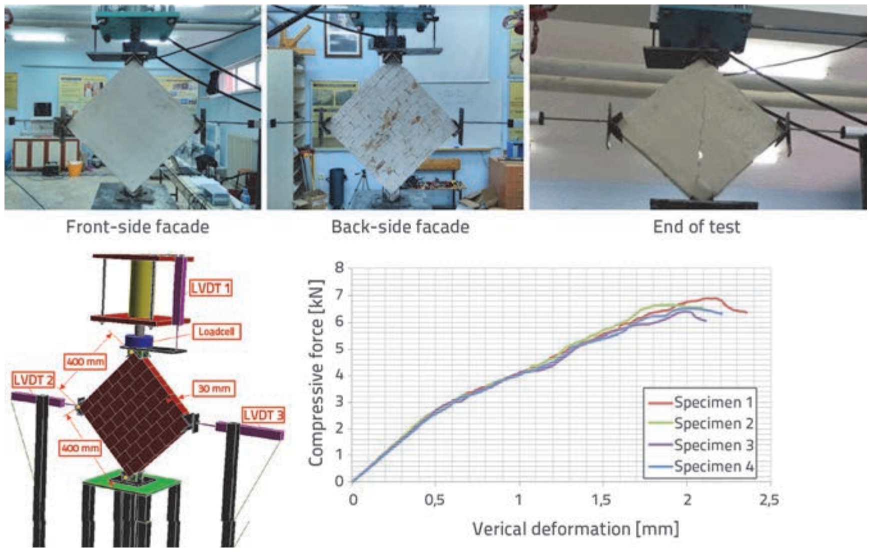


Figure 6. Compressive force - vertical displacement graph of brick wall and test setup of brick wall

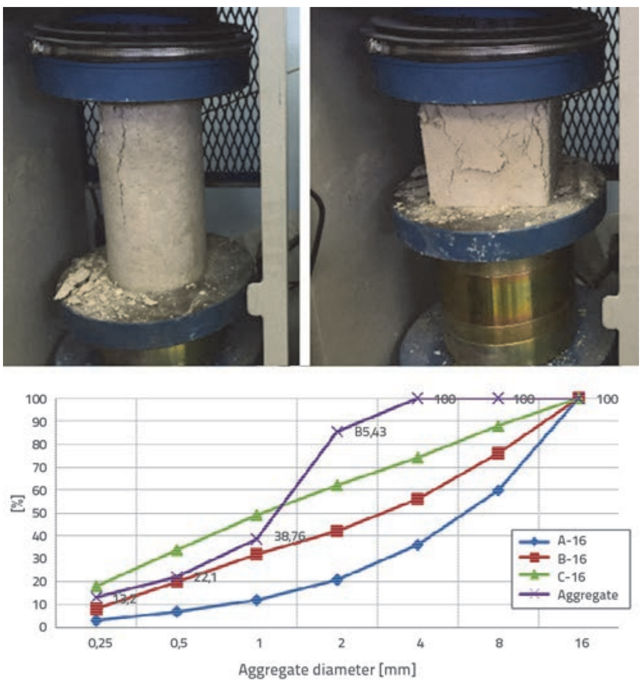


Figure 5. Cylinder and cube compressive strength tests and aggregate grading [22, 24]

Infill brick walls of specimens were tested under diagonal compression. Due to the non-homogenous structure of brick walls, it was very difficult to obtain the modulus of elasticity and Poisson ratio using test data for brick walls. The compressive force-vertical displacement graph of a brick wall is presented in Figure 6 [25].

The average compressive strength of concrete cylinders and cubes, and diagonal compressive strength of brick walls used as test specimens, are given in Table 2. The concrete property testing was conducted according to TS EN-12390-3 [26].

Table 2. Average compressive strength of concrete cylinders and cubes and diagonal compressive strength of brick walls

Specimen	Compressive strength of brick [MPa] (400 x 400 mm)	Compressive strength of concrete [MPa]	
		Cube (200 x 200 x 200 mm)	Cylinder (150 x 300 mm)
1	0.405	8.07	5.85
2	0.392	8.32	6.02
3	0.376	7.38	6.15
4	0.384	7.98	5.62

3. Experimental Program and Testing

The working principle of shaking table used in experiments is to convert rotary motion to linear motion. The specimens were tested under constant axial and sinusoidal cyclic load in order to simulate seismic action. The sinusoidal cyclic load was processed using the DAQ-Card (Labjack-U3) [28]. The general sinusoidal function and graph are shown in Figure 7. The sinusoidal function equation is given in Eq. (1). Time dependent equation factors are given in Table 3.

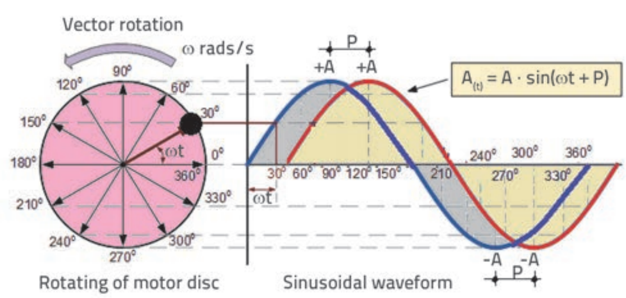


Figure 7. General sinusoidal function and graph

Table 3. Equation factors for the first and second ground motions

1st Ground motion					2nd Ground motion				
Time [s]	A	W	P	f	Time [s]	A	W	P	f
0-2.80	16.52	1.421	12.77	0.704	20.08-22.15	19.87	0.526	67.64	1.902
2.82-5.13	16.45	0.938	6.540	1.067	22.32-26.44	17.22	0.763	-13.45	1.312
5.13-6.39	18.77	0.420	33.03	2.379	26.48-29.36	17.96	0.828	3.561	1.208
6.42-7.54	16.34	0.562	6.874	1.780	29.54-31.39	16.88	0.845	95.93	1.183
7.57-8.99	19.30	0.299	9.044	3.341	31.51-32.64	19.46	0.608	74.44	1.644
9.01-9.61	18.90	0.304	-0.629	3.290	32.64-34.42	19.29	0.607	73.98	1.648
9.64-11.27	19.09	0.318	-10.27	3.143	34.45-36.65	17.97	0.560	106.6	1.787
11.32-12.35	17.72	0.667	37.36	1.500	36.67-37.59	16.90	0.666	40.86	1.501
12.36-13.86	17.16	0.753	25.57	1.328	37.65-38.52	16.43	0.610	83.16	1.640
13.90-15.61	18.56	0.870	22.10	1.150	38.58-40.70	17.97	0.486	77.32	2.056
15.67-17.19	18.19	1.054	73.65	0.949	40.75-41.97	18.26	0.495	124.3	2.019
17.29-18.91	15.43	1.162	26.57	0.861	42.04-45.00	17.60	0.604	6.203	1.656

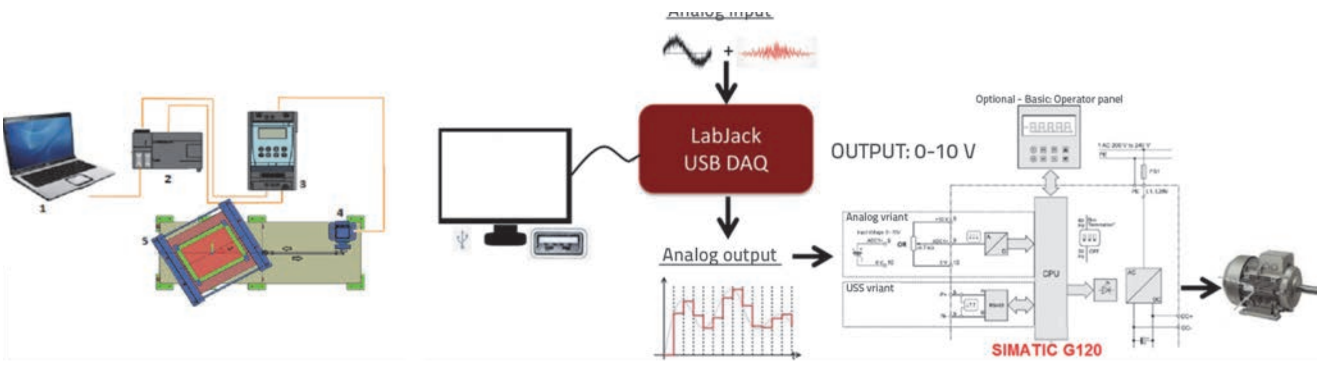


Figure 8. Actual block diagram of control system (1-Computer, 2- Labjack-U3, 3-Simatic-G120, 4-Motor+ Gear Speed Reducer, 5-Shaking Table)

$$A(t)=A\cdot Sin[(2\cdot \pi \cdot t/W)+P] \quad (1)$$

where:
ω - Angular velocity of motor disc
A(t) - Displacement value of shaking table
t - Time of ground motion
A - This value is the height at top of the waves, in A(t)
W - This value is the time it takes to complete a cycle
f - This value is the number of cycles per time unit
P - The PhaseShift of 0 sets $A_{(t)}$ is equal to 0 at t=0

The PhaseShift of "π" sets Y is equal to its maximum when t=0. This value is used at the sinusoidal function equation as radians. Main shaking-table parameters are given in Table 4. The actual block diagram for experiments is shown in Figure 8.

Specimens were tested in vertical position, under constant axial load, on the shaking table. The first specimen (reference specimen) was placed at 0 degrees (Figure 9), the second specimen was placed at 30 degrees (Figure 10), the third specimen was placed at 45 degrees (Figure 11), and the fourth specimen was placed at 60 degrees (Figure 12) on the shaking table.

Table 4. Main parameters for shaking table

Parameters	Values
Size of the platform	80 mm x1200 mm
Maximum mass of load	1500 kg
Maximum platform displacement	±20 mm
Maximum platform acceleration	±4 g
Frequency	0~50 Hz
Maximum engine power	4 kW
Maximum output torque of gear speed reducer	100518 mNm
Maximum input rotational speed of gear speed reducer	3000 rpm
Maximum output rotational speed of gear speed reducer	380 rpm

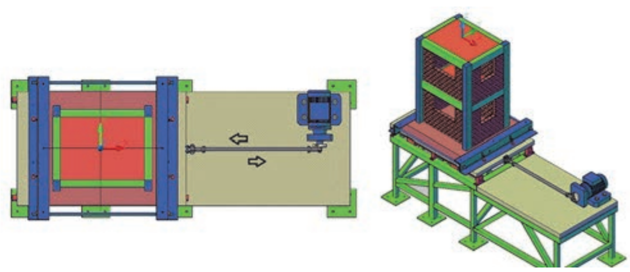


Figure 9. 3D and plan view of Specimen 1 (angle: 0°)

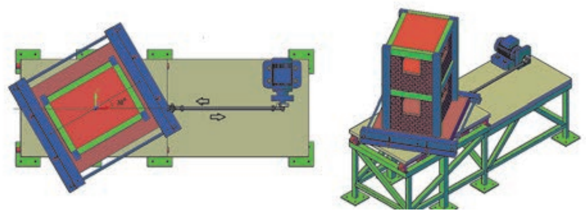


Figure 10. 3D and plan view of Specimen 2 (angle: 30°)

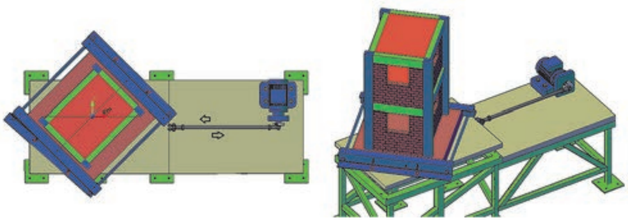


Figure 11. 3D and plan view of Specimen 3 (angle: 45°)

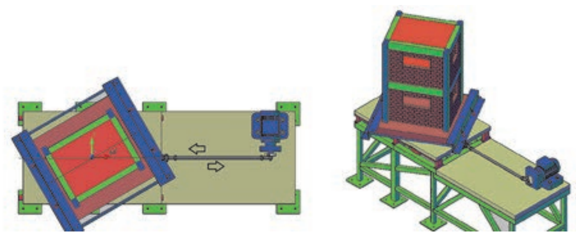


Figure 12. 3D and plan view of Specimen 4 (angle: 60°)

Acceleration data for test frames were measured during experiments using ADXL345 accelerometers (Figure 13). These accelerometers were used to determine acceleration at each storey level.

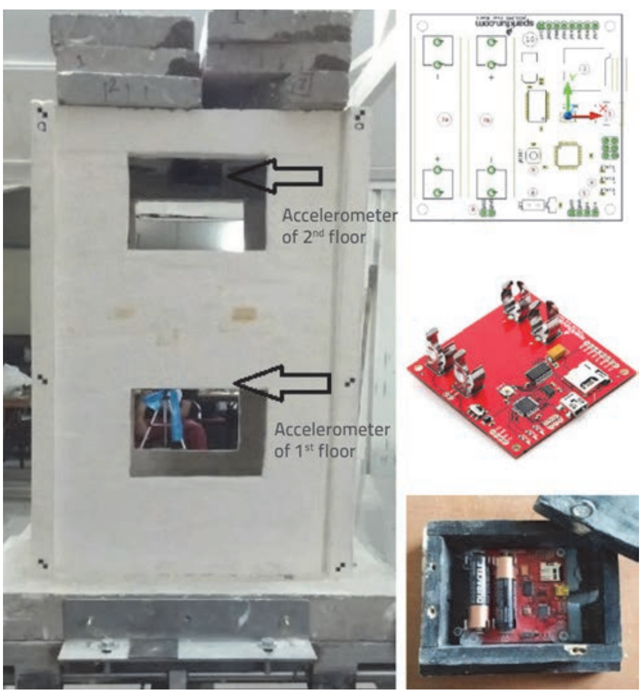


Figure 13. Accelerometer positions and accelerometer (ADXL345 evaluation board)

The ADXL345 is a complete 3-axis acceleration measurement system with a selectable measurement range of ±2 g, ±4 g, ±8 g, or ±16 g. It measures both dynamic accelerations resulting from motion or shock, and static accelerations [28]. The shake table accelerations were measured in both X & Y directions. Before the tests started, accelerometers were calibrated, which also involved image processing. Rather than being placed parallel to the shaking table, accelerometers were placed parallel to the specimens. Linear voltage displacement transducers (LVDT) were not used in experiments because specimens were placed angularly in the shaking table, and the vertical and horizontal displacements of the specimens were large at failure mode.
Specimens were tested for various ground motion values on the shaking table until failure. Specimens 1 and 4 were tested at the 1st ground motion. Specimen 2 was tested at the 1st and 2nd ground motions, while Specimen 3 was tested at the 1st and 2nd ground motions, and once again at the 1st ground motion. These ground motions are shown in Figure 14.

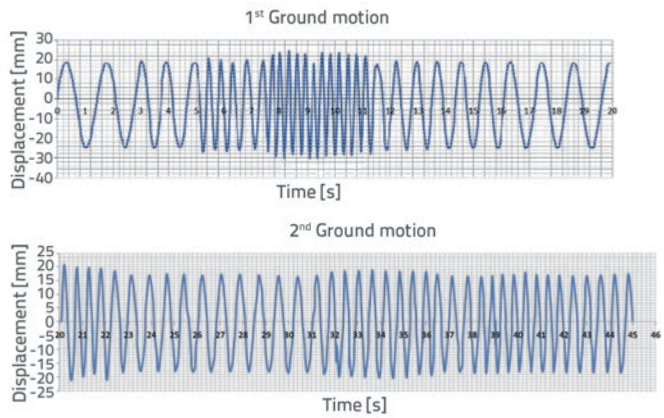


Figure 14. Various ground motion on shaking table

4. Discussion and test results

Acceleration data on the 1st storey and 2nd storey levels, in the X direction and Y direction, were measured on the specimens. The measured acceleration data for Specimen 1, Specimen 2, Specimen 3, and Specimen 4, are shown in Figure 15, Figure 16, Figure 17, and Figure 18, respectively.

Specimen 1:
The first specimen was the reference frame (Specimen 1) placed 0 degrees on shaking 7 table and tested to see the reference behavior for comparison purposes. According to Figure 15, this 8 test was begun at 2 sec and finished at 14.2 sec. The first cracks occurred as shear cracks at the corners of the window opening at the 1st and 2nd storeys at 7.51 s and 7.53 s (Figure 19.a and Table 5). Later on, at Specimen 1, shear cracks occurred at the end point of the left column at 7.66 s and at the end point of the right column at 7.72 s (Figure 19-b and Table 5).
The hinge formations occurred on the column-beam-column joint (left) of the 1st storey at 7.86 s and on the column-beam-column

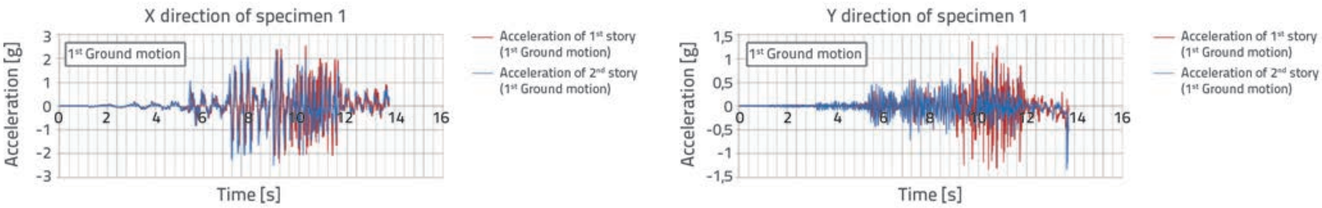


Figure 15. Acceleration data of Specimen 1 (0°)

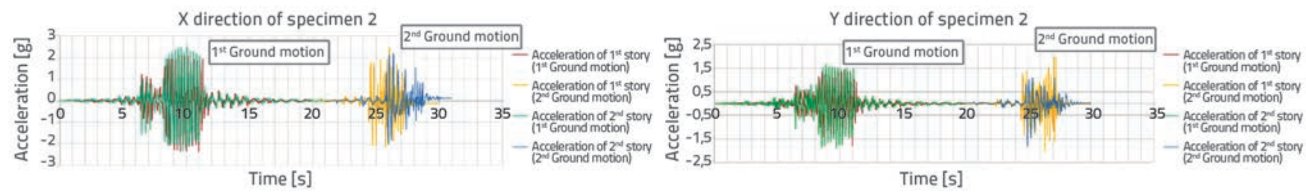


Figure 16. Acceleration data of Specimen 2 (30°)

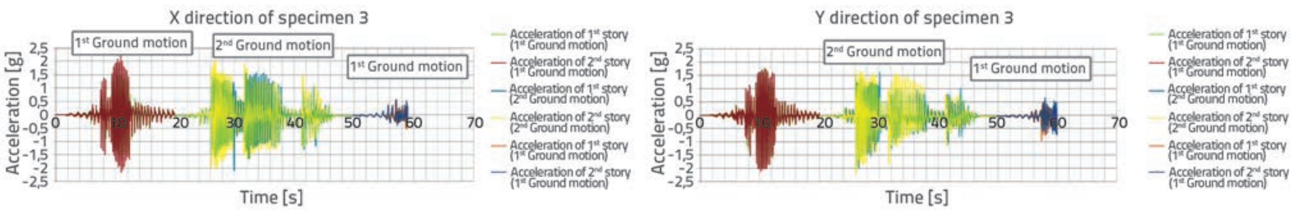


Figure 17. Acceleration data of Specimen 3 (45°)

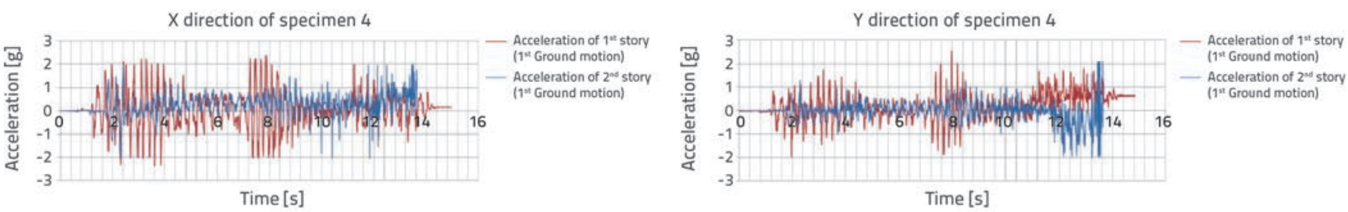


Figure 18. Acceleration data of Specimen 4 (60°)

joint (right) of 1st storey at 9.56 s. Diagonal shear cracks occurred on two sides of brick wall of the window opening of the 2nd storey at 9 seconds. Shear cracks occurred at the window opening of the 1st and 2nd storeys. Specimen 1 was completely destroyed by collapse of the 1st storey at the end of the test (Figure 20).

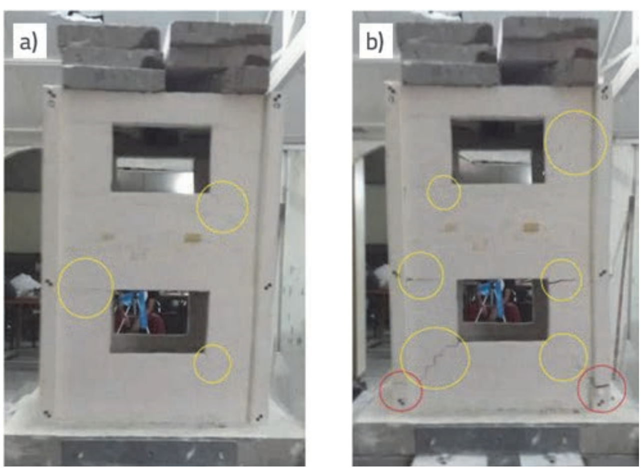
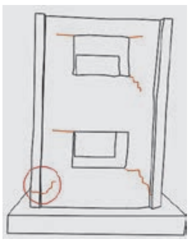
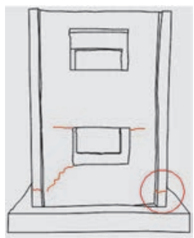
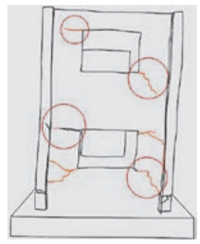
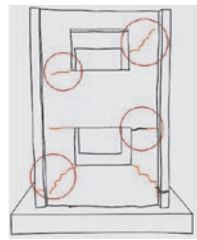


Figure 19. a) Brick walls of Specimen 1; b) Columns of Specimen 1 where first cracking was observed

Figure 20. Failure mode for Specimen 1 (0°)

1st ground motion stage: The maximum negative acceleration value of the first-storey amounted to - 2.39 g at 9.18 s and the maximum positive acceleration value of the first-storey amounted to 2.53 g at 10.28 s in the X direction. The maximum negative acceleration value of the first-storey amounted to - 1.32 g at 10.41 s and the maximum positive acceleration

Table 5. First cracks of Specimen 1

Specimen No 1			First frame crack				First wall crack			
			Forward		Backward		Forward		Backward	
Position of the specimen [angle]	Storey	Direction	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]
0°	1	X	7.66	0.30	7.75	-1.38	7.51	-1.64	7.63	1.40
		Y		-0.06		-0.02		0.11		-0.02
	2	X	7.72	-2.06		-1.16	7.53	0.48	7.6	0.89
		Y		-0.17		-0.36		0.20		-0.21
	Figures									
Figures of failure are not to scale; they are based on the photo.										

value of the first-storey amounted to 1.33 g at 9.73 s in the Y direction.

The maximum negative acceleration value of the second-storey amounted to -2.49 g at 8.49 s and the maximum positive acceleration value of the second-storey amounted to 2.38 g at 9.03 s in the X direction. The maximum negative acceleration value of the second-storey amounted to -0.703 g at 7.15 s and the maximum positive acceleration value of the second-storey amounted to 0.83 g at 13.2 s in the Y direction.

Specimen 2:

The second specimen was placed 30 degrees on the shaking table. Specimen 2 was 2 tested with 1st and 2nd ground motions. According to Figure 16, this test was begun at 0 sec and 3 finished at 28.70 sec. The first cracks occurred as shear cracks at the bottom left and top right corners of the window opening of the 1st and 2nd storeys at 6.43 s and 6.45 s (Figure 21-a and Table 6). The first cracks occurred at the forward ground motion. Later on, the other cracks occurred as shear cracks at the top left and bottom right corners of the window opening of the 1st and 2nd storeys at 6.54 s and 6.55 s (Figure 21-b and Table 6). These cracks occurred at the backward ground motion. Shear cracks occurred at the end point of the right column at 7.41 s (Figure 21-b and Table 6). Specimen 2 did not completely collapse at the end of the test.

1st ground motion stage: The maximum negative acceleration value of the first-storey amounted to -2.37 g at 10.98 seconds and the maximum positive acceleration value of the first-storey amounted to 2.15 g at 9.4 seconds in the X direction. The maximum negative acceleration value of the first-storey amounted to -1.79 g at 10.98 seconds and the maximum positive acceleration value of the first-storey amounted to 1.47 g at 10.37 second in the Y direction. The maximum negative acceleration value of the second-storey amounted to -2.32 g at 9.70 seconds, and the maximum positive acceleration value of the second-storey amounted to 2.51 g at 9.36 seconds in the X direction. The maximum negative acceleration value of the second-storey amounted to -1.87 g at 8.54 seconds, and the maximum positive acceleration value of the second-storey amounted to 1.68 g at 8.86 seconds in the Y direction.

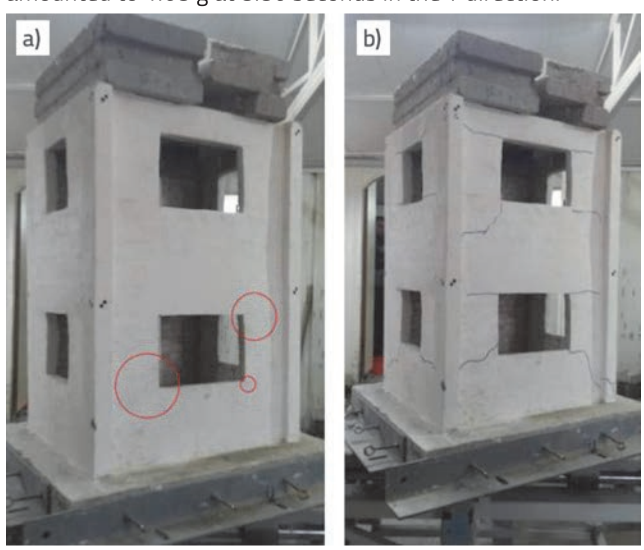
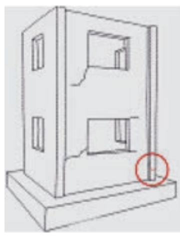
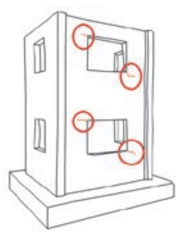
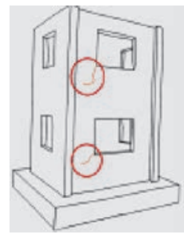


Figure 21. a) first cracks at Specimen 2 occurred at the 1st ground motion; b) damage at the end of the 1st ground motion

Table 6. First cracks at Specimen 2

Specimen No 2		Storey	Direction	First frame crack				First wall crack			
				Forward		Backward		Forward		Backward	
				Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]
Position of the specimen [angle]	30°	1	X	7.41	0.16	24.41	-0.93	6.43	-0.25	6.54	0.2
			Y		0.40		-0.63		0.02		-0.27
		2	X		-0.14		0.09	6.45	-1.2	6.55	0.84
			Y		-0.32		-0.12		-1.07		-0.1
		Figures									
Figures of failure are not to scale; they are based on the photo.											

At the 2nd ground motion stage, hinge occurred on the long façade at columns-base joints and wall-base joints, and shear cracks occurred under and at the corner of the window opening on the other short façade of Specimen 2 at 16.95 seconds. In addition, separation of the brick wall from the RC frame above the window opening is shown in Figure 22. Cases of damage by the forward and backward movement of the shaking table are shown in Figure 22-a and Figure 22.b, respectively.

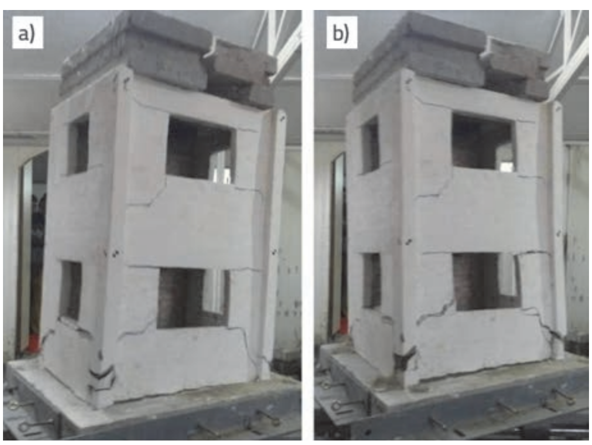


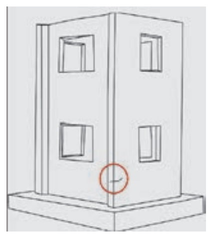
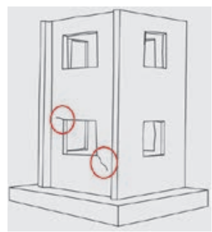
Figure 22. Specimen 2 suffered damage in the forward and backward movement of shaking table

The main damage to Specimen 2 occurred at the column-base joints in form of plastic hinge. Besides, torsional effect occurred at all frames on Specimen 2. Because brick infill walls of the 1st storey were completely destroyed, the soft storey irregularity was observed at Specimen 2 (Figure 23).

Figure 23. Failure mode for Specimen 2 at the end of the 2nd stage of ground motion

2nd ground motion stage: The maximum negative acceleration value of the first-storey amounted to -2.07 g at 24.72 s, and the maximum positive acceleration value of the first-storey amounted to 2.44 g at 26.05 s in the X direction. The maximum negative acceleration value of the first-storey amounted to -2.03 g at 26.35 s, and the maximum positive acceleration value of the first-storey amounted to 1.97 g at 27.07 s in the Y direction. The maximum negative acceleration value of the second-storey amounted to -1.98 g at 25.95 s and the maximum positive acceleration value of the second-storey amounted to 2.19 g at

Table 7. First cracks at Specimen 3

Specimen No 3	Storey	Direction	First frame crack				First wall crack			
			Forward		Backward		Forward		Backward	
			Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]
Position of the specimen [angle] 45°	1	X	6.54	-0.25	7.13	-0.20	6.54	-0.25	7.13	-0.20
		Y		0.22		0.13		0.22		0.13
	2	X		-0.16		-0.20		-0.16		-0.20
		Y		0.16		-0.11		0.16		0.11
	Figures									

Figures of failure are not to scale; they are based on the photo.

26.36 s in the X direction. The maximum negative acceleration value of the second-storey amounted to -1.83 g at 24.94 s, and the maximum positive acceleration value of the second-storey amounted to 1.09 g at 25.35 s in the Y direction.

Specimen 3:

The third specimen was placed at 45 degrees on a shaking table. Specimen 3 was tested by the 1st (20 s) and 2nd (25 s) ground motions, and once again by the 1st ground motions (10 s). Different colours were used to mark the cracks on the specimen to distinguish the 1st ground motion (blue) at the end of the stage, from the 2nd ground motions (red) at the end of the stage. The 2nd ground motion started at 20 s and finished at 45 s. The 1st ground motion restarted at 50 s and finished at 60 s.

The first cracks occurred as shear cracks at the bottom left and top right corners of the window opening of the 1st storey at 6.54 s (Figure 24 and Table 7). The shear cracks occurred at the end point of the left column at 6.54 s (forward ground motion) and right column at 7.128 s (backward ground motion). These cracks occurred only at the corners of the window openings at the 1st ground motion at the end of the stage (Figure 24 and Table 7). The shear cracks and bending cracks occurred at the columns of the frame (Figure 24 and Table 7). Specimen 3 did not collapse at the end of the 1st stage of ground motion.

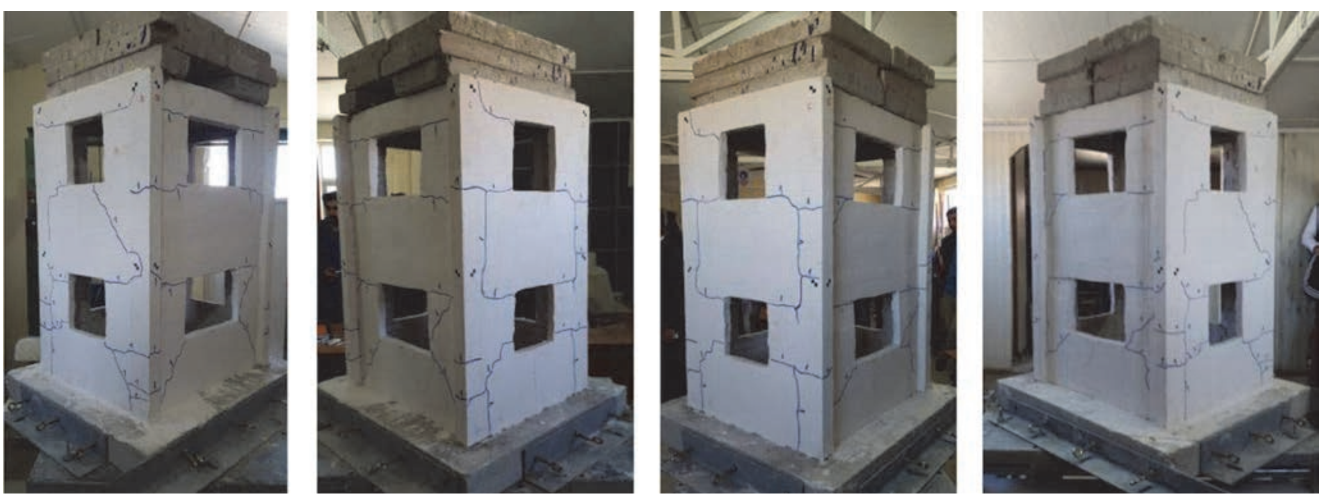


Figure 24. Failure mode for Specimen 3 (45°) at 1st ground motion stage

Figure 25. Failure mode for Specimen 3 at 2nd ground motion stage

Figure 26. Failure mode for Specimen 3 at the end of repeated 1st stage of ground motion

The 1st storey of Specimen 3 did not completely collapse at the end of the 2nd stage of ground motion (Figure 25). But the 1st storey suffered major damage. The top brick wall part of the window opening of the 1st storey collapsed. Besides, at the 2nd stage of ground motion, the plastic hinge started to occur on the column-base joints and at the column-beam-column joints. These joints suffered major damage. The short column irregularity was observed and the shear cracks and bending cracks reached the columns. Besides, torsional effect occurred at all frames.

2nd ground motion stage: The maximum negative acceleration value of the first-storey amounted to -2.08 g at 29.91 s, and the maximum positive acceleration value of the first-storey amounted to 1.56 g at 33.61 s in the X direction. The maximum negative acceleration value of the first-storey amounted to -1.99 g at 26.67 s, and the maximum positive acceleration value of the first-storey amounted to 1.61 g at 30.16 s in the Y direction. The maximum negative acceleration value of the second-storey amounted to -2.04 g at 26.85 s, and the maximum positive acceleration value of the second-storey amounted to 2.05 g at 26.75 s in the X direction. The maximum negative acceleration value of the second-storey amounted to -2.2 g at 26.18 s, and the maximum positive acceleration value of the second-storey amounted to 1.64 g at 26.87 s in the Y direction.

At the repeated 1st stage of ground motion, the plastic hinge reached column-beam-column joints and column-base joints at 8.5 s, and Specimen 3 collapsed completely at the level of the 1st storey at the end of the test (Figure 26). Because torsional effect occurred at all frames, this specimen collapsed completely at the end of the test.

Repeated 1st stage of ground motion: The maximum negative acceleration value of the first-storey amounted to -0.52 g at 58.85 s, and the maximum positive acceleration value of the first-storey amounted to 0.55 g at 56.97 s in the X direction. The maximum negative acceleration value of the first-storey amounted to -0.95 g at 57.36 s, and the maximum positive acceleration value of the first-storey amounted to 0.54 g at 57.86 s in the Y direction. The maximum negative acceleration value of the second-storey amounted to -0.41 g at 57.29 s, and the maximum positive acceleration value of the second-storey amounted to 0.58 g at 57.1 s in the X direction. The maximum negative acceleration value of the second-storey amounted to

-0.75 g at 59.98 s, and the maximum positive acceleration value of the second-storey amounted to 0.668 g at 57.98 s in the Y direction.

Specimen 4:

The fourth specimen was placed at 60 degrees on the shaking table. Specimen 4 was tested by applying the 1st ground motion. First cracks were observed at each façade window corner of the 2nd storey as shear cracks. They occurred at the column-beam joint of the 2nd storey at 1.96 s as hinge formations (Figure 27 and Table 8). Shear cracks occurred at the end point of the column of the 1st storeys at 2.03 s and column-beam joint of the 2nd storey at 2.25 s (Figure 27 and Table 8). As can be seen in Figure 27, the second storey damage was greater compared to that of the first storey. The plastic hinge formations occurred at the column-beam-column joints of the 2nd storey at the end of the 2nd ground motion. Diagonal shear cracks occurred at the window corner of all brick walls. All brick walls collapsed at the end of the test (Figure 28). The hinge formation occurred on column-beam-column joints and column-base joints of Specimen 4 at 11 seconds.

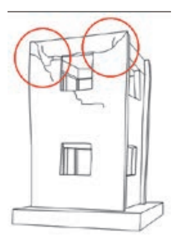
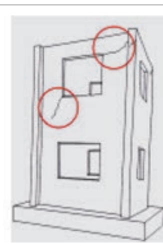
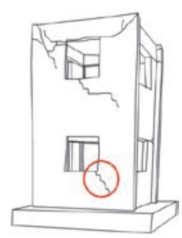
1st ground motion stage: The maximum negative acceleration value of the first-storey amounted to -2.36 g at 3.61 seconds, and the maximum positive acceleration value of the first-storey amounted to 2.36 g at 7.86 seconds in the X direction. The maximum negative acceleration value of the first-storey amounted to -1.97 g at 1.96 seconds, and the maximum positive acceleration value of the first-storey amounted to 2.35 g at 7.98 seconds in the Y direction. The maximum negative acceleration value of the second-storey amounted to -2.05 g at 2.28 seconds, and the maximum positive acceleration value of the second-storey amounted to 1.93 g at 2.41 seconds in the X direction. The maximum negative acceleration value of the second-storey amounted to -1.01 g at 3.71 seconds, and the maximum positive acceleration value of the second-storey amounted to 1.28 g at 8.48 seconds in the Y direction.

Maximum positive-negative accelerations and failure diagrams, based on experimental results, are given in Table 9.

As to maximum positive and negative accelerations:

- Specimen 1 (0 degrees) collapsed at the 1st ground motion. Specimen 1 reached expected acceleration in the X direction.

Table 8. First cracks at Specimen 4

Specimen No 4		Storey	Direction	First frame crack				First wall crack			
				Forward		Backward		Forward		Backward	
				Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	Time [s]	Acceleration [g]
Position of the specimen [angle]	60°	1	X	2.03	-0.81	1.96	1.98	1.96	1.98	2.03	-0.81
			Y		0.48		-1.97		-1.97		0.48
		2	X		-0.20		-1.29		-1.29		-0.20
			Y		0.05		0.75		0.75		0.05
		Figures						 		 	

Figures of failure are not to scale; they are based on the photo.

Figure 27. First cracks for Specimen 4 (60°) at various directions

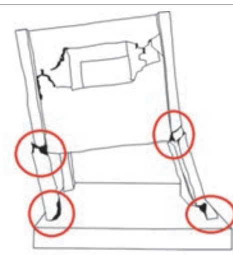
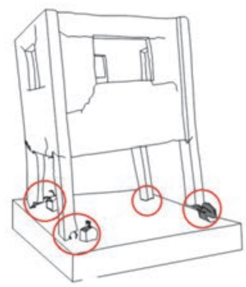
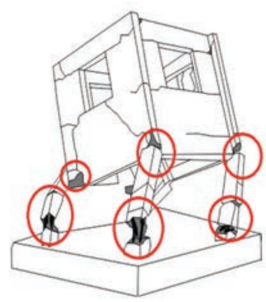
Figure 28. Failure mode for Specimen 4

Because brick walls of the 1st storey collapsed out of plane, accelerations in the Y direction increased more than expected, (especially at first storey level) compared to accelerations in the X direction.

- Specimen 2 (30 degrees) collapsed at the 2nd ground motion. Specimen 2 reached expected accelerations in the X and Y directions and achieved higher accelerations in the X direction compared to the Y direction.
- Specimen 3 (45 degrees) collapsed at the repeated 1st ground motion. Approximately the same acceleration values in the X and Y directions were reached.
- Specimen 4 (60 degrees) collapsed at the 1st ground motion. Approximately the same maximum positive and negative acceleration values in the X and Y directions were reached.

The diagonal shear cracks intensively occurred on all specimens at the window opening of all infill brick walls. 1st storeys of these specimens were completely destroyed at the end of the test.

Table 9. Max positive and negative accelerations of specimens and specimen failure diagrams

Specimen No / angle		Ground motion No	Storey	Direction	Max positive acceleration		Max negative acceleration		Failure diagram
					Time [s]	Acceleration [g]	Time [s]	Acceleration [g]	
1	0°	1	1	X	10.28	2.53	9.18	-2.39	
				Y	9.73	1.33	10.41	-1.32	
			2	X	9.03	2.38	8.49	-2.49	
				Y	13.2	0.83	7.15	-0.703	
2	30°	1	1	X	9.4	2.15	10.98	-2.37	
				Y	10.37	1.47	10.98	-1.79	
			2	X	9.36	2.52	9.70	-2.32	
				Y	8.86	1.68	8.54	-1.87	
		2	1	X	26.05	2.44	24.72	-2.07	
				Y	27.07	1.97	26.35	-2.03	
			2	X	26.36	2.19	25.95	-1.98	
				Y	25.35	1.09	24.94	-1.83	
3	45°	1	1	X	10.13	1.70	11.19	-1.74	
				Y	10.72	1.73	9.9	-1.97	
			2	X	10.89	2.26	10.98	-2.17	
				Y	10.77	1.75	10.16	-2.12	
		2	1	X	33.61	1.56	29.91	-2.08	
				Y	30.16	1.61	26.67	-1.99	
			2	X	26.75	2.05	26.85	-2.04	
				Y	26.87	1.64	26.18	-2.2	
		1	1	X	56.97	0.547	58.85	-0.523	
				Y	57.86	0.535	57.36	-0.949	
			2	X	57.1	0.578	57.29	-0.414	
				Y	57.98	0.668	59.98	-0.754	
4	60°	1	1	X	7.86	2.362	3.615	-2.365	
				Y	7.984	2.353	1.96	-1.97	
			2	X	2.41	1.93	2.28	-2.05	
				Y	8.48	1.28	3.71	-1.01	

5. Conclusion

In this study, 3D-RC frames were tested on the shaking table at different angles to define dynamic behaviour of the structure. The specimens produced featured two storeys, 3D system, one bay, and 1:6 geometric scale. The specimens were tested at various ground motions on shaking table until failure. The first cracks observed at specimens during the testing are summarized below:

- The first specimen cracks occurred simultaneously at the frame and infill brick walls (except for Specimen 2).
- The first cracks at Specimen 2 occurred at infill brick walls and the frame.
- According to test results, failure mechanisms of specimens can be summarized as follows:
- Plastic hinge occurred at column-beam-column joints of Specimen 1. Shear cracks were observed at the brick infill walls of Specimen 1.
- The main damage to Specimen 2 occurred in form of plastic hinge at column-base joints. Besides, the torsional effect occurred at all frames on Specimen 2. Because brick infill walls of the 1st storey were completely destroyed, the soft storey irregularity was observed on Specimen 2. Also, all brick infill walls were affected by shear cracks under and at the corner of the window opening.
- The column-base and the column-beam-column joints of Specimen 3 were affected by major damage. Columns at Specimen 3 were affected by the short column irregularity, shear cracks, and bending cracks. Because the torsional effect occurred at all frames, this specimen collapsed completely at the end of the test.
- Plastic hinge was observed at the column-beam-column joints and column-base joints of Specimen 4. The slab of the 2nd storey collapsed due to failure of the slab-beam connections. Also, all brick walls collapsed at the end of the test. Besides, both 1st and 2nd storeys of the Specimen 4 were completely destroyed.

Soft storey irregularities were observed on all specimens. The damage could generally be classified as the flexural and shear behaviour of columns, and torsional modes at RC frames. The shaking table test results show that the plastic hinge mechanism occurred on all specimens at both column-beam joints and column-base joints. Besides, the brick walls of 1st storeys of all specimens collapsed out of plane. Test results also show that the test specimens placed at different angles have shown different failure mechanisms in the X and Y direction.

Since the samples were not produced according to the design and construction rules given in TEC-2007 [29] and TS-500 [30], the observed damage of tested samples reflects the damage caused by seismic action.

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