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Inventory survey of the 2003 Zemmouri Algeria earthquake: Case study of Dergana City

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Experimental and Analytical Investigations of Seismic Pounding of Adjacent 14-Story Reinforced Concrete Buildings Damaged in 1985 Mexico Earthquake

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Scientific paper

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Abstract
Drop-weight tests and static loading tests of RC frames made of polypropylene fiber-reinforced concrete are conducted to observe shock resistance performance and residual ductility. Experimental variables are fiber content and mass of the drop weight. In the impact test, the maximum drifts of the specimens are proportional to the mass of the drop weight although several collisions occur due to rebounding and the maximum acceleration is not always increased as the mass increases. In a static loading test, the initial stiffness is improved and crack lengths in the hinge areas of the columns are reduced by mixing the polypropylene fibers.

1. Introduction
Control of displacement response during large earthquakes is required in recent performance-based structural designs. In the 1985 Mexico Earthquake, a 14-story RC residential building collapsed due to resonance with long-period motion and pounding between neighboring building units (Bertero 1986; Isobe et al. 2012; Chujo et al. 2016). Several analytical investigations have been conducted for this building. Many examples of damage such as pounding at the expansion joint of two units or very narrow spaces between neighboring buildings have been reported in the US and New Zealand (Kasai and Maison 1997; Cole et al. 2010, 2014).

A number of studies have been conducted on the impact behavior of reinforced concrete structures. These studies dealt with relatively simple members such as the drop-weight test of simple beams and the pounding between bridge girders. On the other hand, only a few were conducted for rigid frame specimens where the damping due to the plastic deformation of the frame is one of the influential factors. Examples of these studies are Woodson’s research on structural collapse caused by explosion (Woodson 1999) and Xiao’s collapse test by removing first-story columns (Xiao 2015). These studies provide variable information but the conditions differ significantly from those considered in this paper in that the RC members pound in relatively low velocity ranging from 0.5 to 5 m/s. The analyses of the 14-story RC building by Chujo et al. (Chujo et al. 2016) attempted to simulate the local contact behavior by inserting linkage elements between the gap of two neighboring building units (Fig. 1) although the stress-displacement relationship model used for the linkage elements was defined based on several assumptions. This study therefore aims at sampling the stresses and displacements at the collision part of RC frames subjected to drop-weight tests.

In addition, the effectiveness of fiber-reinforced ce-
mentitious composites (FRCC) is examined to improve the structural performance. There are also many studies on the impact test of FRCC. Most of these studies discussed the influence of strain rate on the strength, stiffness, and ductility of FRCC without steel reinforcing bars (e.g., Naaman and Gopalaratnam 1983; Gopalaratnam and Shah 1986; ACI 1994; Banthia et al. 1996; Wang et al. 1996; Manolis et al. 1997; Bindiganavile et al. 2002). One study of impact on structural columns made of FRCC is Burrell’s blast pressure tests (Burrell 2015), but the impact load and velocity are significantly larger than those in structural pounding.

This study observes the behavior of one-story and one-span frame specimens made of ordinary concrete and polypropylene fiber-reinforced concrete subjected to an impact load of low velocity (5 m/s) and discusses vibration characteristics, residual restoring force characteristics, crack lengths, and spalled area of cover concrete.

2. Test

2.1 Specimens

Table 1 summarizes the specifications of the specimens and Fig. 2 shows the geometry. Experimental variables are fiber content in the concrete and the mass of the drop weight. A one-story/one-span frame specimen consists of a flat slab, a pair of columns, and a fixing base. The specimen refers to a low seismic resistant RC frame based on old design guidelines. The specimen also refers to a non-structural slender column supposed in a contemporary architectural design. The column cross section is 100 mm × 100 mm with four longitudinally deformed bars of 10 mm diameter and shear reinforcing round bars of 4 mm diameter with 80 mm spacing. The clear height is 900 mm (i.e., shear span ratio = 4.5) and the flat slab is 100 mm thick.

Table 1 Specimens.

| Specimen | Material                  | Target displacement (%) | Mass of drop weight (kg) |
|----------|---------------------------|-------------------------|--------------------------|
| N0       | Plain concrete (N)        | —                       | —                        |
| N1       | Polypropylene fiber-reinforced concrete (PP) | 1.5 | 45.5 |
| N2       | Polypropylene fiber-reinforced concrete (PP) | 4.0 | 141.9 |
| N3       | Polypropylene fiber-reinforced concrete (PP) | 6.0 | 219.4 |
| PP0      | Polypropylene fiber-reinforced concrete (PP) | — | — |
| PP1      | Polypropylene fiber-reinforced concrete (PP) | 1.5 | 45.5 |
| PP2      | Polypropylene fiber-reinforced concrete (PP) | 4.0 | 141.9 |
| PP3      | Polypropylene fiber-reinforced concrete (PP) | 6.0 | 219.4 |

Table 2 Concrete mixtures.

| PP fiber (Vol. %) | W/C (%) | W | C | S | G | SP/C (%) |
|-------------------|---------|---|---|---|---|----------|
| PP                | 1.2     | 47 | 185 | 394 | 809 | 869 | 0.5 |

F: Foundation, N: Plain concrete, PP: Polypropylene fiber-reinforced concrete, SP: Super plasticizer.

2.2 Materials

Two kinds of materials were used: plain concrete (denoted “N”) and polypropylene fiber-reinforced concrete (denoted “PP”). Table 2 summarizes the concrete mix proportion. The same mix proportion was adopted for both N and PP. The fiber used in this study was polypropylene resin monofilament with an embossed surface. This type of fiber has length of 30 mm and equivalent diameter of 0.7 mm. The weight per unit volume is 0.91 g/cm³ and the maximum tensile strength is 500 N/mm². The fiber volume fraction was 1.2% and the mix proportion of the water, cement, sand, gravel, and super plasticizer was not changed. The concrete was mixed by a gravity-type mixer and the polypropylene fibers were added by hand after the mixture was completed. Table 3 summarizes the results of the material tests of the concretes and steel bars.

2.3 Drop-weight tests

Impact tests were conducted with three different masses of drop weights. Figure 3 shows the instrumentation of the drop-weight tests. Each specimen was rotated 90° and fixed to a concrete block. A counter weight (121.0 kg) is hung to cancel the specimen’s own weight. A drop weight composed of steel plates, whose number can be arbitrary chosen, was hung by a magnet hanger and released from a height of 1.29 m. A constant velocity of 5 m/s was applied at the instance of collision. The masses of the drop weights were 45.5 kg, 141.9 kg, and 219.4 kg. According to the impact tests of beam specimens by
Saatci (2009), the ratio of the energy absorbed by a specimen to the kinetic energy of the drop weight ranges from 0.062 to 0.322, and the ratio depends on the shear reinforcement ratio and the kinetic energy of the drop weight. In this study, the masses of the drop weights were determined based on the assumptions that (1) the ratio of energies is assumed as 0.2; (2) the expected ultimate drifts of the specimens are 1.5%, 4%, and 6%; and (3) the drop height is constant. A load cell of 100 kN capacity was inserted between the specimen and the drop weight. A displacement transducer and an accelerometer were fixed on the slab of the specimen. The sampling frequency was 2 kHz and the duration was one second.

2.4 Static loading tests

After the drop-weight test, the specimens were restored to their initial positions and reversed cyclic static loads were applied by a hydraulic jack to observe residual restoring force characteristics, as shown in Fig. 4. Positive and negative drifts of 0.25%, 0.5%, 1%, 2%, 4%, 6%, and 8% were each applied twice. Here, drift is defined as the ratio of relative displacement between the slab and fixing base to the column height of 900 mm.

3. Test results

3.1 Drop-weight test

(1) Test result

Table 4 summarizes the results of the drop-weight tests. In Table 4, potential energy is calculated by multiplying the mass of the drop weight by the drop height. The load is obtained from the load cell placed on the dropping point of the specimen, the acceleration is measured by an accelerometer fixed on a side of the slab, and the drift by the relative displacement between the fixing base and the slab. The residual drift is defined as the drift at 0.9 seconds after the initial collision of the drop weight. For the drifts and accelerations, data smoothing was executed by using moving averages (i.e., 0.0015 sec. average for 0.0005 sec. sampling). The maximum loads tend to be proportional to the potential energy of the drop weights although some deviations were found.

Figure 5 shows the time histories of drifts and Fig. 6...
the time histories of accelerations. The maximum drifts were: N1 0.47%, N2 4.59%, N3 7.03%, PP1 0.83%, PP2 3.98%, and PP3 6.12%. The maximum drift increases as the drop energy increases. Several pulses were found in the histories of drifts and accelerations between 0.2 and 0.4 seconds because of the rebounding of the drop weight. The maximum accelerations shown in Table 4 are classified into the initial collision, the initial rebounding, and the second rebounding. The maximum accelerations were not always proportional to the mass of drop weight because the damping increased due to the plastic deformation of the specimen as the mass of drop weight increased. The residual drift becomes larger as the drop weight becomes heavier. The residual drifts of PP2 and PP3 made of fiber-reinforced concrete were slightly smaller than those of N2 and N3 although those of N1 and PP1 were small and equivalent.

![Drift (%)](image)

**Table 4 Results of drop-weight tests.**

| Specimen | Mass of drop weight (kg) | Potential energy (Nm) | Maximum load (kN) | Maximum drift (%) | Residual drift (%) | Initial collision | Initial rebounding | Second Rebounding |
|----------|--------------------------|-----------------------|-------------------|------------------|------------------|-----------------|------------------|------------------|
| N1       | 45.5                     | 558                   | 32.2              | 0.47             | 0.05             | 159             | 30               | --               |
| N2       | 141.9                    | 1827                  | 132.7             | 4.59             | 2.64             | 1021            | 159              | --               |
| N3       | 219.4                    | 2841                  | 242.6             | 7.03             | 5.52             | 1069            | 243              | 31               |
| PP1      | 45.5                     | 558                   | 11.1              | 0.83             | 0.08             | 473             | 95               | --               |
| PP2      | 141.9                    | 1827                  | 108.6             | 3.98             | 2.46             | 1034            | 139              | 146              |
| PP3      | 219.4                    | 2841                  | 268.0             | 6.12             | 5.04             | 991             | 193              | 148              |

![Acceleration (m/s²)]

(2) Crack patterns of specimens after the drop-weight test

Figure 8 shows the crack patterns of specimens after the drop-weight test. In Fig. 8, the impact load is input from
the left side of the slab. Significantly, the cracks occurred on the tension sides of the columns and the slab. The number of cracks became larger as the drop weight became heavier. The total numbers of cracks of the PP series were almost equivalent to those of the N series specimens although the crack widths became smaller.

(3) Apparent coefficient of restitution
Calculation of the apparent coefficient of restitution, $e_a$, was based on the test results. In this study, $e_a$ is defined as the ratio of relative velocity, $v_d$, between the slab of the specimen and the drop weight to the drop velocity at the instance of collision (5 m/s). Unlike empirical coefficients of restitution derived from collision tests of a pair of free bodies or rigid body-free body tests, $e_a$ is an apparent value because it partially depends on the stiffness and damping of the RC frame. By comparing $e_a$ with those in previous studies, the influence of the RC frame will be quantified. In this study, displacement and acceleration of the slab were measured while no measuring devices were attached to the drop weight. Hence, the velocity, $v_d$, of the drop weight after the initial rebounding is indirectly estimated by reading pulses in the acceleration data corresponding to the instances of the initial collision and initial rebounding.

In the time histories of acceleration, shown in Fig. 6, several impulses follow after the initial impulse at 0.1 sec. The first set of impulses is regarded as corresponding to the initial collision, the second set to the initial rebounding, and the third to the second rebounding as indicated in Fig. 6. A collision or a rebounding consists of several impulses because several local contacts may have occurred between the uneven concrete surface of the specimen and the drop weight. The time between the initial collision and the initial rebounding is defined as $t_r$ (Fig. 6) and the absolute displacement of the slab at the time of initial rebounding as $\delta_r$. The relationship between $t_r$, $\delta_r$, $v_d$, and gravity acceleration $g$ ($> 0$) are given by Eq. (1)
\[ \delta = - \frac{1}{2} gt^2 \]  

Hence,  

\[ v = \frac{\delta}{t} \]  

Table 5 shows \( t_r, \delta_r, v_d, \) and \( e_a \) of each specimen. 

**Figure 9** shows the relationships between \( e_a \) and the mass of the drop weight. The value of \( e_a \) ranged from 0.128 to 0.355 and tended to decrease as the mass of the drop weight increased although the influence of the PP fiber mixture is insignificant. Jankowski (Jankowski 2010) estimated coefficients of restitution by dropping balls on a rigid plane surface with varied velocities from 0.2 m/s to 4.0 m/s. The coefficients of restitution at 4.0 m/s are 0.45 for concrete and 0.45 for steel, so similar values are expected at 5.0 m/s if the same test conditions were adopted. It is supposed that the values of \( e_a \) were smaller than these values because of the stiffness and damping of the RC frame. The coefficient of restitution of the pounding structures must therefore be estimated in view of the mass and stiffness of the structures, which may be smaller than 0.45.

### 3.2 Static loading test

**Figure 10** shows the relationships between load and drift in the static loading tests. The origin of the drift in **Fig. 10** is defined as the residual drift after the drop-weight test. The hysteresis loops tend to be pinched as the drop weight becomes heavier for both specimens made of ordinary concrete (N series) and polypropylene fiber-reinforced concrete (PP series). This tendency is especially significant in the N series since the polypropylene fibers in the PP series reduce the damage caused by the drop weight. **Figure 11** compares the load-drift relationships between N0, N3, PP0, and PP3 up to 1.0% drift. For N1 and PP1, in which the drop weights are smallest and the residual drifts do not exceed 1%, almost no decrease in stiffness at 1% drift is observed. In contrast, the decrease in stiffness of N2, N3, PP2, and PP3 becomes significant as the drop weight becomes heavier.
(2) Equivalent viscous damping
Figure 12 compares the relationships between equivalent viscous damping and drift. As the drop weight becomes heavier, the equivalent viscous damping becomes smaller, indicating a decrease in the energy absorption capacity of the specimens. The lowest equivalent viscous damping is observed in N3 while those of PP2 and PP3 with the polypropylene fibers are equivalent. Therefore, polypropylene fibers are effective especially when the drop weight is heavier. However, the variety of equivalent viscous damping among the specimens at 8% drift became smaller comparing to those at 4% and 6% drifts.

(3) Crack patterns of specimens after static loading test
Figure 13 shows typical crack patterns of specimens after the static loading test. The number of cracks and area of spalled cover concrete becomes larger as the drop weight becomes heavier. Also, the number of cracks in the hinge areas of the PP series specimens is smaller than in the N series specimens. The start of spalling in the cover concrete of the N series specimens was 4%. In contrast, it was 6% in one of the PP series specimens, behind relative to that of the N series specimens. This is because crack length and spalling of the cover concrete are restrained by the crack bridging effect of the PP fiber.

4. Quantification of crack lengths and spalled area of cover concrete

After the 2000s, optical and digital imaging techniques were developed to detect cracks on the surfaces of RC structures (e.g., Weiss and Olek 2003; Lecompte et al...
These techniques enable non-destructive, non-contact, and remote detection of cracks and are expected to apply to conditions in which direct detection is difficult such as the exterior surfaces of medium- and high-rise buildings. For the imaging technique, crack length is an important index as well as crack width. Compared to crack width, however, the relationship between crack length and damage level of RC structures has not always been clarified. Hence, this section attempts to quantify the crack lengths of specimens and discuss the relationship between the damage induced by impact load and static cyclic load.

### 4.1 Crack lengths

Crack lengths are measured from hinge areas of columns (i.e. 100 mm-height areas at the top and the bottom of the two columns) of the specimens. The crack lengths may vary by the manner in how zig-zag shapes are measured. In this test, a length of approximately 5 mm was adopted as the minimum measuring length, as shown in Fig. 14.

Table 6 summarizes the crack lengths. The second line of Table 6 lists the crack lengths after the drop-weight tests $L_{cr\_drop}$. For specimens of drop weights of 45.5 kg and 219.4 kg (i.e., Specimens N1, N3, PP1, and PP3), $L_{cr\_drop}$ of the PP series are shorter than those of the N series because of the polypropylene fiber mixture. This comparison indicates that the fiber mixture prevents large flexural and shear cracks from forming under the larger impact load. The third to ninth lines of Table 6 list the crack lengths after the static loading test. Figure 15 shows the relationships between the crack lengths and drift. The crack lengths become longer as the drop weight becomes heavier, but the lengths of the PP series specimens are shorter than those of the N series. The effect of the polypropylene fibers in reducing crack length becomes significant as the drop weight becomes heavier.

One of the purposes of quantification of the crack length is to estimate the seriousness of damage that the impact load gives to the structure. As Table 6 indicates, the crack lengths induced by the impact load and the static load are considerably different even if the same level of drift is given. For this purpose, an equivalent static crack length $L_{cr\_eq}$ is introduced. $L_{cr\_eq}$ is defined as crack length of static specimens (i.e. N0 and PP0) at drift corresponding to residual drift of drop weight specimens. The values of $L_{cr\_eq}$ are listed in the eleventh line of Table 6. For Specimen PP3, for an instance, the residual drift at the drop-weight test is 5.04% (the tenth line of Table 6). The crack length $L_{cr\_eq}$ at the static loading test of Specimen PP0 at 5.04% drift is given by interpolating between those at 4% and 6% drifts as Eq. (3) expresses.

![Fig. 14 Minimum measuring unit of crack length and spalled area.](image1)

![Fig. 15 Relationships between crack lengths in hinge areas and drift.](image2)

| Specimen | N0 (--) | N1 (45.5 kg) | N2 (141.9 kg) | N3 (219.4 kg) | PP0 (--) | PP1 (45.5 kg) | PP2 (141.9 kg) | PP3 (219.4 kg) |
|----------|---------|-------------|--------------|--------------|----------|---------------|---------------|---------------|
| Drop weight test $L_{cr\_drop}$ | 2.37 | 3.75 | 2.73 | 7.49 | 2.20 | 2.29 | 3.35 | 5.17 |
| Drift = 0.25% | 3.53 | 4.32 | 3.06 | 7.26 | 3.68 | 3.61 | 3.99 | 5.81 |
| Drift = 0.5% | 4.61 | 5.00 | 3.57 | 8.36 | 4.92 | 4.83 | 4.54 | 6.26 |
| Drift = 1% | 5.63 | 6.61 | 5.12 | 9.95 | 6.97 | 6.69 | 6.26 | 8.72 |
| Drift = 2% | 9.99 | 13.54 | 9.93 | 14.87 | 12.36 | 11.35 | 10.80 | 12.06 |
| Drift = 4% | 19.86 | 22.40 | 15.91 | 22.45 | 16.74 | 13.24 | 16.08 | 16.20 |
| Drift = 6% | 30.37 | 30.37 | 19.72 | 32.95 | 20.69 | 18.46 | 19.00 | 22.02 |
| Drift = 8% | 28.55 | 28.55 | 20.07 | 32.95 | 20.69 | 18.46 | 19.00 | 22.02 |
| Drift = 4% | 28.55 | 28.55 | 20.07 | 32.95 | 20.69 | 18.46 | 19.00 | 22.02 |
| Drift = 6% | 30.37 | 30.37 | 19.72 | 32.95 | 20.69 | 18.46 | 19.00 | 22.02 |
| Drift = 8% | 28.55 | 28.55 | 20.07 | 32.95 | 20.69 | 18.46 | 19.00 | 22.02 |

$L_{cr\_eq}$ = crack length of static specimens (i.e. N0 and PP0) at drift corresponding to residual drift of drop weight specimens.
\[ L_{cr} \text{ of PP0 at drift 5.04} = L_{cr} \text{ of PP0 at drift 4\%} \]
\[ + (L_{cr} \text{ of PP0 at drift 6\%} - L_{cr} \text{ of PP0 at drift 4\%}) \times (5.04\% - 4\%)/(6\% - 4\%) \]
\[ = 12.36m + (16.74m - 12.36m) \times 1.04\% / 2\% \]
\[ = 14.64m \]

This 14.64 m is given as \( L_{cr, eq} \) of Specimen PP3. Figure 16 shows relationships between \( L_{cr, eq} \), \( L_{cr, drop} \), and mass of drop weight. Comparing to \( L_{cr, eq} \), the crack lengths after the drop-weight test \( L_{cr, drop} \) are considerably smaller, approximately one-third of the \( L_{cr, eq} \), for Specimens N2, PP2, N3 and PP3. These estimations indicate that the impact load results in a smaller amount of crack length comparing to that by the reversed cyclic seismic loading. In other words, the damage due to the impact load must be judge as three times serious as expected by the measured crack lengths.

4.2 Area of spalled cover concrete

Figure 17 shows the relationships between the area of spalled cover concrete and drift. The spalled area is measured as Fig. 14 indicates. The polypropylene fibers drastically reduce the area of spalled cover concrete by 73.1% although no correlation between the area and the mass of the drop weight was observed.

5. Conclusions

Drop-weight tests of RC frames made of plain concrete and polypropylene fiber-reinforced concrete were conducted by applying impact loads of drop weights of varied mass onto the end of a slab. The specimens were then subjected to static loading tests to observe the residual restoring force characteristics. In the drop-weight tests of this study, the maximum accelerations are not always increased when the drop weight became heavier than 141.9 kg because the damping increased due to the plastic deformation of the specimen as the mass of drop weight increased. On the other hand, the maximum drifts and residual drifts tended to be proportional to the mass of the drop weight, and the predominant periods were elongated by damage to the specimens. In the static loading tests, decreases in stiffness and equivalent viscous damping were observed especially for the specimens subjected to larger mass drop weights. The mixture of polypropylene fibers reduced the crack lengths in the hinge areas of the columns and increased the equivalent viscous damping in the static cyclic loading tests. The measured crack lengths indicate that the impact load results in a smaller amount of crack length comparing to that by the reversed cyclic seismic loading. The damage due to the impact load must be judge as three times serious as expected by the measured crack lengths.

Quantification of the effectiveness of the polypropylene fibers will be conducted in future research by means of numerical analysis.

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