Scientific paper

Drop-Weight Impact Loading of Polypropylene Fiber Reinforced Concrete Wall after One-Year Drying Shrinkage

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Abstract

Recent progress in finite element analysis aids the simulation of seismic vibration of an entire reinforced concrete (RC) building structure and indicates that drying shrinkage cracks affect seismic resistance performance. Polypropylene fiber-reinforced concrete (PFRC) is a promising material since the fibers will reduce the cracks and strains under drying shrinkage. This paper attempts to quantify the vibration characteristics of PFRC walls by means of a drop-weight test and finite element analyses. Four wall specimens having the same geometry and bar arrangement are prepared. After a one-year drying shrinkage period, the walls are subjected to impact loading of a constant collision velocity of 5 m/s, using a steel drop weight of 398.8 kg. Shear cracks are observed in the restrained wall made of plain concrete, while cracks are insignificant in the PFRC wall. Three-dimensional (3D) nonlinear finite element analyses are conducted to simulate all behaviors from drying shrinkage cracking up to the time of impact loading, and to estimate the vibration characteristics. The analysis results indicate that the polypropylene fiber content reduces the elongation of the natural period by an average of 13.7%.

1. Introduction

Until now, drying shrinkage cracking of reinforced concrete (RC) has been viewed only as one of the causes of steel bar corrosion or as a problem of external aesthetics. However, several finite element analyses of full-modeled RC buildings, made possible by recent advancement in numerical techniques, indicate that shrinkage cracking probably affects the seismic performances of structures (Kurihara et al. 2017; Kitazawa et al. 2018). Figure 1 shows the seismic behavior of a 22-story RC wall building, analyzed in a study by some of the authors (Kitazawa et al. 2018). Figure 1(a) compares relationships between total drift in the north–south direction and time under SCT1 acceleration recorded in the 1985 Mexico Earthquake (AIJ 1986; Petrovski et al. 1988). The red line represents the case considering the drying shrinkage strain and attains a maximum drift of 0.96%, while the black line, disregarding shrinkage, records 0.54%. The maximum drift is therefore increased by 77% by considering shrinkage. Consequently, the building’s damage is aggravated by the increased cracking and crushed parts (indicated in red), as Fig. 1(c) shows. It should also be noted that a large strain rate of approximately 5.0/second is induced to the finite element during the vibration, as Fig. 1(b) shows.

Conventional seismic resistance measures, such as increasing the cross-sections of columns and beams or adding stiffening members to reduce response drift, may decrease usable floor area and harm aesthetic values. One of the possible alternatives, which need not change the structural geometry, is fiber-reinforced concrete. This study conducts free vibration tests of wall specimens made of polypropylene fiber-reinforced concrete (PFRC) by means of low-velocity drop-weight to quantify how PFRC reduces damage to and improves the vibration characteristics of RC walls sensitive to drying shrinkage. The behaviors of the wall specimens are numerically reproduced by nonlinear finite element analyses, to compare natural period changes in plain concrete and PFRC walls during the vibration that occurs after the drop-weight collision.

2. Test

2.1 Specimen

Table 1 summarizes the specifications of the four wall specimens and Fig. 2 shows the geometry. The experimental variables are the types of concrete, and the restraining of shrinkage deformation. The walls have the same geometry and bar arrangement as those of the "NOP" specimen in a previous experimental study (Iwamoto et al. 2016) in the interests of the analytical investigation in the following section since the static behavior of NOP was analyzed in another previous study (Akai et al. 2017). The wall is 1050 × 700 × 70 mm with

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plain reinforcing bars of 4 mm diameter with 50 mm spacing. The reinforcement ratio is 0.36%. The column cross-section is 150 × 150 mm, with four longitudinally deformed bars of 6 mm diameter (0.57%) and plain shear reinforcing bars of 4 mm diameter with 50 mm spacing (0.34%). Specimens N0 and NR are of plain concrete, while P0 and PR use PFRC. This mixture is presented in Fig. 2, which is the same as that used in the authors’ previous study (Makita et al. 2018). An early strength Portland cement is used, the intention being to exaggerate the drying shrinkage strain. The plain concrete is made of the same mixture, except for the fiber. The fiber used in this study was polypropylene resin monofilament with an embossed surface. This type of fiber has a length of 30 mm and an equivalent diameter of 0.7 mm. Its weight is 0.91 g/cm³ and its maximum tensile strength is 500 N/mm². The fiber volume fraction is 1.2%.

### 2.2 Drying condition and strength development

The wall specimens are subjected to two kinds of drying shrinkage conditions. Specimens N0 and P0 are subjected to a 21-day drying period without any restraint. The period of 21 day is selected to avoid an exaggerated shrinkage crack extension while to ensure sufficient developments of the shrinkage strains. Figure 3 shows the relationships between the average shrinkage strains and the material day, and Fig. 4 shows the temperature and relative humidity of the corresponding period. The shrinkage strain before the drop-weight test is 1.344 × 10⁻³ for the plain concrete of N0 and 0.993 × 10⁻³ for the PFRC of P0. The average temperature during this period is 24.2°C and the average relative humidity is 71.0%.

Figure 5 shows the development of the compressive strength, the elastic modulus, the strain corresponding to the compressive strength, and the tensile strength. Each value attains more than 90% of its 21-day property within seven material days.

| Specimen | Drying period (day) | Restraint | Concrete Kind | Strength (N/mm²) | Shrinkage strain (×10⁻³) | Max. drift (%) | Residual drift (%) | Max. load (kN) | Max. strain rate (/s) |
|----------|---------------------|-----------|---------------|------------------|------------------------|----------------|------------------|---------------|---------------------|
| N0       | 22                  | None      | Plain         | 46.2             | 1.344                  | 0.649          | 0.057            | 717.2         | 38.5                |
| P0       | 21                  | None      | PFRC          | 50.0             | 0.993                  | 0.635          | -0.015           | 780.1         | --*                 |
| NR       | 372                 | Restrained| Plain         | 40.7             | 1.877                  | 0.637          | 0.150            | 775.5         | 5.3                 |
| PR       | 373                 | Restrained| PFRC          | 50.7             | 1.031                  | 0.687          | 0.102            | 764.3         | 27.1                |

*Strain data of P0 is lost because of measuring difficulties.

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Fig. 1 Comparison of seismic behavior of 22-story RC wall building, considering and not considering drying shrinkage (Kitazawa et al. 2018).

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### Table 1 Wall specimens and test results.

- **Without shrinkage**
  - Drift (%): 0.8
  - Strain rate (/second): 0.2
- **With shrinkage**
  - Drift (%): 0.7
  - Strain rate (/second): 0.3

(a) Relationships between total drift in NS direction and time

(b) Relationships between maximum strain rate and time

(c) Deformations and distributions of cracks and crushed parts (in red) at maximum drift
Conversely, NR and PR are subjected to one year’s drying and restraining. After casting and the removal of formwork, the top and bottom blocks are fixed to a strong steel reaction wall by eight high-strength bolts, each.
applying 179 kN of tension to restrain the shrinkage deformation of the wall, as shown in Fig. 6(a). Specimens for the free shrinkage tests are prepared, in the form of blocks of size 100 × 100 × 500 mm. Two free shrinkage specimens are prepared for each wall specimen. Two clip gauges of 50 mm-measuring length are installed on each block 24 hours after the casting. The strains are initialized at the time of installation. Figures 7, 8 and 9 show the shrinkage strains, the temperature, the relative humidity, and the developments of material properties. The shrinkage strain before the drop-weight test is 1.877 × 10^{-3} for the plain concrete of NR and 1.031 × 10^{-3} for the PFRC of PR. The average temperature during this period is 17.0°C and the average relative humidity is 65.2%. The shrinkage strain of the PFRC is equivalent to that at 21 days, and almost half that of the plain concrete.

Figure 10 shows the relationships between compressive stress and strain of the concretes, obtained by cylinders of 100 mm diameter and 200 mm height. The numbers in the legends denote the material day. The PFRCs of P0 and PR present higher stresses in the post-peak stage than the plain concretes, but the pre-peak behaviors are almost identical.

Figure 11 shows the relationships between load and crack opening displacement of three-point bending specimens of 100 × 100 mm cross-section and 400 mm clear span with a central groove of 20 mm depth. Four volume ratios of the polypropylene fiber content are used, of 0%, 0.6%, 1.2%, and 1.8%, although only two of those four ratios are used for the wall specimens. As expected, the residual load becomes larger as the volume ratio becomes larger. Figure 12 shows the back-analyzed
tension softening characteristics of the plain concrete for N0 and NR (0%) and the PFRC for P0 and PR (1.2%). The residual stress of the latter is 0.67 N/mm², which is maintained until the fiber length is completely pulled out from the concrete matrix. These characteristics will be used for the finite element analyses in the following section.

Fig. 7 Relationships between drying shrinkage strains and material day of concrete, for NR and PR.

Fig. 8 Relationships between temperature, relative humidity and material day of concrete, for NR and PR.

Fig. 9 Development of compressive strength, elastic modulus, strain corresponding to compressive strength, and tensile strength of concrete, for NR and PR.

Fig. 10 Relationships between compressive stress and strain of concretes.

Fig. 11 Relationships between load and crack opening displacement curves of three-point bending tests.

Fig. 12 Tension softening characteristics input trilinear for FEM based on back-analysis.
2.3 Drop-weight tests

The drop-weight tests are conducted using the instrumentation shown in Figs. 2 and 6(c). The instrumentation is intended to induce at least a strain rate of 5.0/second to the specimen, in accordance with the value obtained in the building analyses shown in Fig. 1(b). Each specimen is rotated 90° and fixed to a concrete block. Axial forces of 188 kN in total are applied by two externally aligned high-strength bars tensioned by two hydraulic jacks on the top block. A drop weight composed of steel plates integrated by four 23 mm-diameter high-strength bolts is suspended by a magnet hanger and released from a height of 1.29 m. A constant velocity of 5.0 m/second is applied at the instant of collision. The mass of the drop weight is 398.8 kg. According to impact tests on beam specimens by Saatci and Vecchio (2009), the ratio of the energy absorbed by a specimen to the kinetic energy of the drop weight ranges from 6% to 32% and depends on the shear reinforcement ratio and the kinetic energy of the drop weight. In this study, the mass of the drop weight is determined based on the assumptions that: (1) the ratio of energies is 15%; (2) the expected ultimate drift of the wall specimen is 0.5%, and; (3) the drop height is constant. Four displacement transducers are fixed to the specimen to measure the horizontal and vertical displacements of the top block (d1 and d2) and the slip and separation of the bottom block (d3 and d4). The drift is defined by Eq. (1):

\[
\text{Drift} = \frac{(d1\text{ (mm)} - d3\text{ (mm)} - d4\text{ (mm)} \times 1500\text{ mm})}{1775\text{ mm}}
\]

Equation (1) indicates that the drift is calculated from the top drift (d1) by subtracting the slip (d3) and the rotation (d4 \times \text{height/width}). The maximum separation measured by d4 at the instance of drop collision is 1.4 mm. The sampling frequency is 5 kHz and the duration is 0.6 second. Table 1 summarizes the test results. Figures 13 and 14 show time histories of the drifts and loads, respectively. The maximum drifts are: N0, 0.649%; P0, 0.635%; NR, 0.637%; and PR, 0.687%. The residual...
drifts, defined as average drifts between 0.1 and 0.6 seconds, are: N0, 0.053%; P0, -0.005%; NR, 0.158%; and PR, 0.087%. The maximum loads are: N0, 717.2 kN; P0, 780.1 kN; NR, 775.5 kN; and PR, 764.3 kN. The maximum drifts and loads of the four walls are almost equivalent, while the residual drift of NR is the largest among the four walls.

Figure 15 shows the crack patterns. Unlike FRCs with high volume ratio of fine fibers, the external appearance of cracks of the PFRC does not differ to that of an ordinary concrete very much. Before the drop-weight tests, cracks of 0.04 mm width are found only in NR. After the test, a flexural crack along the boundary between the wall and the bottom block is observed in all the specimens. The crack widths widen to 0.10 mm, although the existing cracks are not extended. No concrete crushing or bar rupturing is observed, as shown in Fig. 6(b).

3. Analyses of tested specimens

3.1 Modeling

A 3D mesh is prepared as shown in Fig. 16(b), to numerically reproduce the walls’ behaviors. The element size, approximately 50 mm, is selected because the size is preferably equal or larger than the fiber length (30 mm) and the maximum aggregate size (15 mm) in the interest of uniformity. A nonlinear finite element program is used that can analyze the response history over time (Naganuma et al. 2004; Sato and Naganuma 2007, 2014). The concrete part, the load cell, and the drop weight are modeled by eight-node hexahedral elements (total 3570 elements) and the longitudinal steel bars in the columns and the external high-strength bars are modeled by two-node truss elements (total 272 elements). The shear reinforcements are modeled by embedded smeared reinforcement in the quadrilateral concrete elements. The

|                | N0                  | P0                  | NR                  | PR                  |
|----------------|---------------------|---------------------|---------------------|---------------------|
| **Test**       |                     |                     |                     |                     |
| **Before drop-weight test** | 0.05 | 0.05 | 0.05 | 0.05 |
| **Analysis**   |                     |                     |                     |                     |
| **Test**       |                     |                     |                     |                     |
| **After drop-weight test** | 0.10 | 0.10 | 0.10 | 0.10 |
| **Analysis**   |                     |                     |                     |                     |

Fig. 15 Cracks before and after drop-weight test (cracks smaller than 0.04 mm in width are erased).
static cyclic response of this model is compared with Iwamoto and Tsuda’s (2016) test result in Fig. 16(a). A total of 338 joint elements are inserted between the bottom block and the fixing boundary, to provide a rigid reaction under compression and free separation under tension, which is experimentally measured by the displacement transducer d4 as shown in Fig. 2. Twelve joint elements are inserted between the top block, the load cell, and the drop weight, to model strain rate-dependent contacts. All the elements are defined by a linear interpolation function, so that analytical stability in the nonlinear state is enhanced. The total degrees of freedom of the model are 16556. Figures 16(c), (d), (e), and (f) show the constitutive models of concrete (Naganuma et al. 2004) for the compression side, the tension side, the compression–tension transfer paths, and the shear transfer paths, respectively.

The strain rate dependencies of the compressive and tensile strengths of concrete are considered based on research by Fujikake et al. (2006), and the yield stress of steel based on research by Hosoya et al. (1996), as shown in Fig. 16(g). The polypropylene fiber reinforcement effects are modeled as tension softening characteristics in trilinear input data Fig. 12. The residual tension softening stress will ultimately be lost when the 30 mm-long fiber is completely pulled out, but the maximum crack widths does not exceed 0.6 mm within the range of present study. The analyses in this paper adopt the smeared crack model associated with fixed crack formulation, so the shear transfer model along the cracked surface is applied. For concrete crack propagation, the discretization method of crack distribution is applied (Sato and Naganuma 2007, 2014). For the stress–strain relationship of steel in a bar, Ciampi’s model involving the Bauschinger effect is used (Fig. 16(h)) (Ciampi et al. 1982).

The shrinkage cracking is analyzed prior to the drop-weight dynamic analyses. 69.5% of the shrinkage strains shown in Figs. 3 and 7 are input to each specimen. This ratio is evaluated by CEB-FIP Model Code (CEB-FIP 1990) considering different conditions between the shrinkage block and wall specimen. The major difference is their geometries, which are considered by a term $A_s/A$, where $A_s$ is cross section while $A$ peripheral length. Material age increments are 0.05 days up to seven days, and of 0.175 days up to one year. Tensile creep is considered by accumulating tensile strains step by step (Hong et al. 2015; Ida et al. 2016; Kato et al. 2019).

The dynamic analyses are conducted by applying gravity acceleration of 9807 mm/s² to the entire model. The stiffness of the two-node joint elements between the top block, the load cell and the drop weight is determined by adopting a stiffness equivalent to either smaller stiffness of the finite element in the two sides. For ex-
ample, the joint element between the concrete top block and the steel load cell always adopts the former. The joint element stiffness is renewed step by step, depending on the stiffness change of concrete element. The load cell, which has a cylindrical geometry in reality, is modeled by only two hexahedral elements so that the element size is consistent with the specimen. The coarseness of the load cell mesh is compensated by calibrated property of the joint elements. This approach is useful especially when the collision behavior of whole structure model of a building is analyzed such like pounding of two neighboring buildings (Chujo et al. 2016), where a fine meshing is difficult or unpractical.

The time increment is 0.0001 second. The Newmark-β time integration method is adopted, with parameters $\beta = 0.25$ and $\gamma = 0.5$, with uniform 1% damping proportional to the initial stiffness assumed for the natural period of 0.00856 second, which is evaluated by eigenvalue analysis using the subspace method. Figures 13, 14, and 15 compare the time histories of drift and load and the crack patterns between the tests and the analyses. Cracks with widths smaller than 0.04 mm are erased from Fig. 15 since they are invisible to the eye. The analyses simulate well the overall behaviors as well as the significant cracking in NR. The crack pattern of NR differs from the other three walls in the following two points: (1) A relatively large crack opening of 0.06 mm width appears on the top part before the drop-weight test and (2) a 0.09 mm diagonal crack occurs in the midst after the test. The angles and locations of the cracks do entirely not match with those of the test but may reduce the stiffness comparing to the walls made of the PFRC.

### 3.2 Results

Figure 17 compares the load–drift curves between the tests and the analyses. The load peaks at a drift of around 0.03% and descends rapidly. This behavior differs considerably from the relatively ductile response observed in the static loading shown in Fig. 16(a). The load begins to descend when the contact between the drop weight and the top block is lost, and the kinetic energy, which has been transferred from the former to the latter, drives the wall to further drift by inertia with the load descending. At the time around 0.5 to 0.6 seconds, the second peak due to rebounding of the drop weight is observed. This second peak is not enough to induce further drift and the drift soon turns to decrease.

Figure 18 compares the strains in column bars between the tests and the analyses. The strains are measured on the longitudinal bars at the boundary between the columns and the bottom block, as shown in Fig. 2. In the drying shrinkage period, the average strains of N0, P0, and PR are all less than $1.0 \times 10^{-3}$ while that of NR exceeds $1.0 \times 10^{-3}$ (Fig. 18(a)). The strain of N0 and P0 are almost zero. The reason is supposed that the compression due to the shrinkage is cancelled by tension due to the cracking at this location. A similar cancelation must have occurred in NR and PR, but the cracking tension may have become larger than the compression after a year. The analyzed strains do not agree with the tests except for PR but have a qualitative tendency that the largest strain is observed in NR.

Figure 18(b) shows the strain on the tension side column at the drop-weight test, and Fig. 18(c) the compression side. Note that the test data for P0 is lost because of measuring difficulties. Residual plastic strains larger than $5.0 \times 10^{-3}$ are observed on the tension sides of N0 and NR. On the other hand, compressive plastic residual strain is observed on the tension side of PR. The maximum strain rates derived from the measured strains in the tests are 38.5/second for N0, 5.3/second for NR, and 27.1/second for PR (Table 1). The maximum strain rates at the same location computed by the analyses are 8.4/second for N0, 17.8/second for P0, 14.6/second for NR, and 4.7/second for PR. These values cannot directly be compared with the value (5.0 m/second) of the building analysis shown in Fig. 1 because the strain rate usually becomes larger as the mesh size becomes smaller (approximately 500 mm mesh for the building model in Fig. 1, while 50 mm for the wall specimen in Fig. 16). However, these strain rates indicate that the drop-weight test reproduces at least a part of the dynamic behavior of real building under seismic vibration.

Figure 19 compares crack propagations between NR and PR from the maximum load step to the maximum drift step. The polypropylene fiber evidently reduces the number of cracks in PR, when compared to NR.

Figure 20 shows spectra derived from the drift–time relationships of the test shown in Fig. 13. The spectra are classified into three parts: 0.075–0.150
second, 0.150–0.225 second, and 0.225–0.300 second. The initial collision period, from time zero to 0.075 s, is excluded because it contains relatively large plastic deformation. The peak amplitude is found in the period between 0.01 and 0.03 seconds in each specimen.

Figure 21(a) shows the first to sixth eigenmode vectors of the wall model evaluated by the subspace eigenvalue analyses, considering the degraded stiffness of the plasticized concretes and steels. The third mode is the shear–flexural deformation in this study, with other modes being the out-of-plane or twisting deformations.

Consequently, Fig. 21(b) shows the time histories of the third mode’s natural period. The natural period ranges between 0.019 and 0.024 seconds, which matches the peaks of spectrums in Fig. 20. As mentioned above, the initial elastic natural period of this model is 0.00856 second. The period is then doubled during the drying shrinkage period and further elongated by the drop-weight impact. The natural periods of N0 and NR are longer than 0.022 second and those of P0 and PR are shorter. PFRC therefore reduces the elongation of the natural period. It should be noted that the natural periods of NR and PR, subjected to one year of shrinkage, are smaller than those of N0 and P0 with 21-day shrinkage.

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| Max. load | 0.2% drift | 0.4% drift | Max. drift |
|-----------|------------|------------|------------|
| NR        |            |            |            |
| PR        |            |            |            |

Fig. 19 Crack propagations of NR and PR (cracks smaller than 0.04 mm width are erased).
This is because tensile creep narrows the opening widths of the shrinkage cracks during the longer drying period. This phenomenon is reported in a study by some of the authors (Sato and Naganuma 2012).

### 4. Parametric analyses

#### 4.1 Parameters

A series of parametric analyses is conducted, using the same 3D model presented in the previous section, to quantify the influence of the parameters on the vibration characteristics of the wall. A total of 18 analysis cases are computed by varying three analytical parameters: (i) concrete material (N: plain concrete and P: PFRC); (ii) collision velocity (2.5 m/second, 5.0 m/second, and 7.5 m/second), and; (iii) drying shrinkage strain ratio (0.5×, 1.0×, and 1.5× that of the test). Each case is denoted in a sequence such as P_75_15 (PFRC wall subjected to 7.5 m/second collision velocity and 1.5× drying shrinkage strain ratio).

| Case   | Material | Collision velocity (m/second) | Maximum shrinkage strain ($\times 10^{-6}$) | Maximum load (kN) | Maximum drift (%) | Natural period (microsecond) |
|--------|----------|-------------------------------|---------------------------------------------|-------------------|------------------|-------------------------------|
| N 25 05 | Plain concrete | 2.5                           | 667                                         | 199               | 0.27             | 19.5                          |
| N 25 10 | Plain concrete | 5.0                           | 1333                                        | 231               | 0.33             | 21.7                          |
| N 25 15 | Plain concrete | 7.7                           | 667                                         | 1333              | 0.68             | 23.0                          |
| N 50 05 | Plain concrete | 2.5                           | 2000                                        | 612               | 0.36             | 23.9                          |
| N 50 10 | Plain concrete | 5.0                           | 2000                                        | 603               | 0.58             | 24.0                          |
| N 50 15 | Plain concrete | 7.7                           | 1333                                        | 648               | 0.86             | 26.8                          |
| N 75 05 | Plain concrete | 2.5                           | 667                                         | 675               | 0.96             | 22.4                          |
| N 75 10 | Plain concrete | 5.0                           | 667                                         | 875               | 1.06             | 23.9                          |
| N 75 15 | Plain concrete | 7.7                           | 2000                                        | 941               | 1.25             | 27.6                          |
| P 25 05 | PFRC      | 2.5                           | 382                                         | 208               | 0.26             | 16.6                          |
| P 25 10 | PFRC      | 5.0                           | 763                                         | 240               | 0.29             | 19.3                          |
| P 25 15 | PFRC      | 7.7                           | 1145                                        | 567               | 0.55             | 18.9                          |
| P 50 05 | PFRC      | 2.5                           | 382                                         | 230               | 0.30             | 20.9                          |
| P 50 10 | PFRC      | 5.0                           | 763                                         | 598               | 0.60             | 20.8                          |
| P 50 15 | PFRC      | 7.7                           | 1145                                        | 627               | 0.65             | 21.2                          |
| P 75 05 | PFRC      | 2.5                           | 382                                         | 879               | 0.92             | 18.9                          |
| P 75 10 | PFRC      | 5.0                           | 763                                         | 939               | 0.97             | 21.4                          |
| P 75 15 | PFRC      | 7.7                           | 1145                                        | 934               | 1.03             | 21.4                          |

This phenomenon is reported in a study by some of the authors (Sato and Naganuma 2012).

![Drift spectrums derived from drop-weight test.](image.png)

**Fig. 20** Drift spectrums derived from drop-weight test.

![Eigenmode vectors](image.png)

**Fig. 21** Results of eigenvalue analysis.
A one-year drying period is assumed. The PFRC shrinkage strain is reduced by 57%, based on the test shown in Fig. 7. Table 2 summarizes the conditions and results of the parametric analyses. Relationships between maximum loads, maximum drift, the natural period and the parameters are shown in Fig. 22. The natural period is the value at 0.5 second after the collision. The horizontal axis of each figure is the parametric ratio of the drying shrinkage strain to that of the test. The various lines and markers distinguish the collision velocity, and the colors indicate the concrete material (black for plain concrete and red for PFRC). Load-time responses, drift-time responses, and load–drift relationships of three typical cases (P_25_10, P_50_10, and P_75_10) are shown in Figs. 23(a), (b), and (c), respectively.

4.2 Influence of kinds of concrete materials

Figure 22(a) shows that the kind of concrete material slightly affects the maximum load. On the other hand, Fig. 22(b) shows that the maximum drifts of the PFRC walls are always smaller than those of the plain concrete walls, regardless of velocities or shrinkage strains. The reductions of the drifts become larger as the shrinkage strain ratio becomes larger. The average reduction ratios are 4.2%, 10.7%, and 19.7% for 0.5×, 1.0×, and 1.5× the shrinkage ratios, respectively. The reduction is almost constant at around 11%, if averaged in each collision velocity (i.e., 11.1%, 13.5%, and 9.9% for velocities of 2.5 m/s, 5.0 m/s, and 7.5 m/s, respectively). The natural periods of the PFRC walls are always shorter than those of the plain concrete, as shown in Fig. 22(c). Unlike the maximum drift, the reduction ratio does not always become larger corresponding to the shrinkage strain ratio.
and the collision velocity. The average reduction ratio of the natural period due to use of PFRC is 13.7%. Figure 24 depicts the typical effectiveness of PFRC; the numbers of cracks of in the case of P_75_15 before and after the collision are significantly reduced, compared to case N_75_15. This reduction of cracks results in reduced elongation of the natural periods of the PFRC walls.

4.3 Influence of shrinkage strain ratio
Figure 22(a) shows that the maximum load increases as the shrinkage strain ratio increases. Comparing to the 1.0× strain, the maximum load is decreased by 4.5% on average for 0.5× strain and increased by 3.8% on average for 1.5× strain. The maximum drift significantly increases as the shrinkage strain ratio increases, as shown in Fig. 22(b). Compared to the 1.0× strain, maximum drift is decreased by 9.2% on average for 0.5× strain and increased by 14.0% on average for 1.5× strain. As mentioned in the previous section, the influence of the shrinkage strain ratio is more significant for plain concrete than for PFRC. Figure 22(c) shows that the natural period is also increased, as the shrinkage strain increases. Comparing to the 1.0× strain, the natural period is decreased by 10.7% on average for 0.5× strain and increased by 8.6% on average for 1.5× strain.

4.4 Influence of collision velocity
Figures 22(a) and 23(a) show that the maximum load increases by approximately 340 kN with each velocity increment of 2.5 m/second. Similarly, Figs. 22(b) and 23(b) show that the maximum drift increases by approximately 0.35% with each velocity increment. Figure 23(c) shows these same tendencies. On the other hand, the influence of the velocity on the natural period is not as great as the influence of the kind of material and the shrinkage strain ratio. This observation implies that the shrinkage strain controlled by the polypropylene fiber could reduce the elongation of the natural period regardless of the magnitude of the dynamic impact within the conditions of this study.

5. Conclusions
One-year drying shrinkage under the restrained condition induces significant cracking to the RC walls made of plain concrete while the cracks of the PFRC walls are reduced under the same condition. The following conclusions are drawn, based on the drop-weight tests and the finite element analyses of the RC walls.
(1) PFRC also reduces the cracks induced by the drop-weight collision and reduces the elongation of the natural period.
(2) Parametric analyses with varied shrinkage strains, collision velocities, and kinds of concrete materials indicate that PFRC reduces the elongation of the natural period by an average of 13.7%.

The finite element analyses employed in this study present close agreements with the experimental load and drift responses. The analyses also reproduce the overall crack patterns and crack widths although some discrepancies are found regarding to the crack locations. On the other hand, the present method cannot precisely predict the steel bar strain and the rebound behaviors. In future research, efforts will be spent to improve the accuracy and then the method will be applied to seismic response analyses of buildings designed in accordance with current design codes.

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