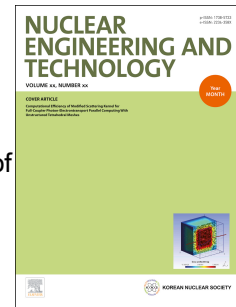


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Seismic performance evaluation of reactor containment building considering effects of concrete material models and prestressing forces

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Abstract

The reactor containment building (RCB) in nuclear power plants (NPPs) plays an important role in protecting the reactor systems from external loads as well as preventing radioactive leaking. As we witnessed the nuclear disaster at Fukushima Daiichi (Japan) in 2011, the earthquake is one of the major threats to NPPs. The purpose of this study is to evaluate effects of concrete material models and prestressing forces on the seismic performance evaluation of RCB in NPPs. A typical RCB designed in Korea is employed for a case study. Detailed three-dimensional nonlinear finite element models of RCB are developed in ANSYS. A series of pushover analyses are then performed to obtain the pushover curves of RCB. Different capacity curves are compared to recognize the influence of different material models on the nonlinear behavior of RCB. Additionally, the effects of prestressing forces on the seismic performances of the structure are also investigated. Moreover, a set of damage states corresponding to damage evolutions of the structures is proposed in this study.

Keywords: nuclear power plant; three-dimensional finite element model; pushover analysis; concrete model; prestressing force

1. Introduction

The number of nuclear power plants (NPPs) has been growing around the world and playing as the second major energy source for decades. However, the Chernobyl (Ukraine, 1986) and Fukushima Daiichi (Japan, 2011) nuclear disasters have taught us well about the serious impact of the nuclear disaster on the natural environment, human beings, and economic values. The radioactive leakage from a nuclear containment

structure can cause catastrophic consequences. Thus, the reactor containment building (RCB) is considered the most important structure in nuclear power plants.

The seismic performance of NPP structures is commonly evaluated using probabilistic approaches [1-9], in which the influences of input structural variables or earthquakes need to be investigated sufficiently. Effects of uncertainty in different modeling parameters to RCBs were addressed in previous studies [10-15]. Also, many studies studied the effects of earthquake characteristics on the performance of NPP structures such as mainshock-aftershock [16, 17], near-fault motions [18-20], far-fault motions [21, 22], site-specific ground motions [23, 24], duration of motions [25], and frequency content [26, 27]. Recently, Nguyen et al. [28] studied the efficiency of various structural modeling schemes on evaluating seismic performance and fragility of an RCB. They emphasized that the linear analysis might underestimate the probability of damage of RCB at a given earthquake intensity when compared to the nonlinear analysis.

However, effects of prestressing forces are not properly considered in most of the numerical analysis of such studies. Even though a limited number of studies considered the presence of prestressing forces in their numerical models of various RCBs [29-40], they mostly focused on the performance of RCBs against the internal loads or pressures, not seismic effects.

To improve the structural capacity of NPP structures, the use of high-strength concrete materials is a promising solution. Choun and Park [41, 42] investigated the influences of fiber reinforced concrete on the pressure capacity of a prestressed concrete containment vessel (PCCV) structure. They considered two types of fibers, i.e. steel and polyamide. They concluded that the pressure capacity of PCCV with 1% volume of steel fibers was increased by 12% in comparison to a conventional PCCV, while 1.5% volume of polyamide fibers increased the pressure capacity of PCCV by 3%. However, the aforesaid study mainly focused on the ultimate pressure capacity and the failure mechanism under the internal pressure. The seismic response analyses of RCB considering different concrete materials were not systematically conducted yet.

The purpose of this study is to evaluate the effects of various concrete material models and prestressing forces on the nonlinear seismic behavior of RCB. Four different concrete models are considered in this study, namely, high-performance concrete (HPC), steel fiber reinforced concrete (SFRC), polyamide fiber reinforced concrete (PFRC), and normal concrete with a compressive strength of 40 MPa (M40). For numerical analyses,

three-dimensional finite element models (3D FEM) are developed in ANSYS, a commercial software. To evaluate the capacity of RCB, pushover analyses are performed with different material models and with/without prestressing forces. Furthermore, a set of damages states of the non-prestressed and prestressed RCB structures are proposed, which can be useful for a fragility analysis of such structure.

2. Modeling of RCB

2.1. Structural configuration

RCB of one of the Korean NPPs is selected for numerical analyses. The reactor containment cylinder has 22.8 m inner radius, 54 m height, and 1.22 m thickness. The inner radius of the dome is 22.8 m, the average thickness is 1.07 m making the final height of dome as 23.5m. Structural dimensions and reinforcement details of the structure are shown in Fig. 1. There are two layers of reinforcement with both layers consisting of vertical and horizontal bars of 18 mm diameter with the spacing of 300 mm. In addition, the RCB wall is prestressed with post-tensioning tendons. The tendons are anchored between alternate buttresses at 180 degrees. All tendons are tensioned from both ends. The details of the prestressing tendons are also shown in Fig. 1. It consists of two layers of the post-tensioning tendons along with the horizontal and vertical directions.

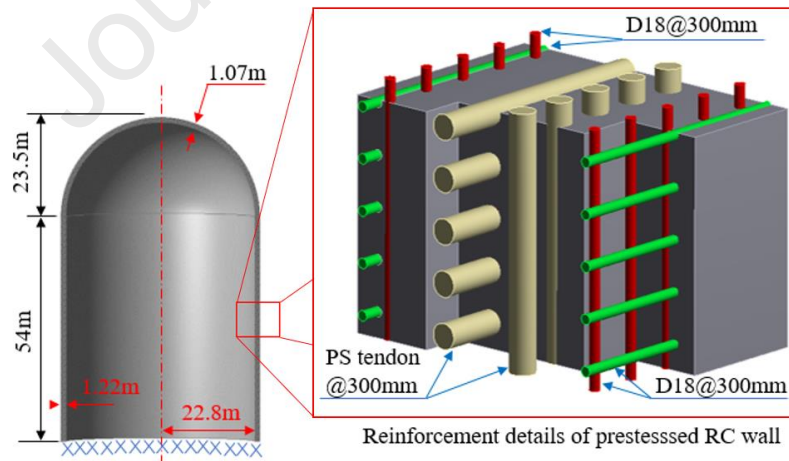


Fig. 1. Dimensions and reinforcement details of RCB

2.2. Material properties

2.2.1. Nonlinear concrete material models

ANSYS [43] provides a large number of material models in its material library. For this study, four isotropic nonlinear concrete material models are used to investigate the effects of different concrete material models on the seismic behavior of RCB. Fig. 2 presents the nonlinear stress-strain relationships of various concrete material models used in this study. The material models considered in this study are high-performance concrete (HPC), steel fiber reinforced concrete (SFRC), polyamide fiber reinforced concrete (PFRC), and plain concrete (M40) with a compressive strength of 40 MPa (referred to as M40). It should be noted that, in addition to a difference in the compressive stress, the tensile stresses and corresponding strains of investigated materials are significantly different. The mechanical properties of concrete models are given in Table 1.

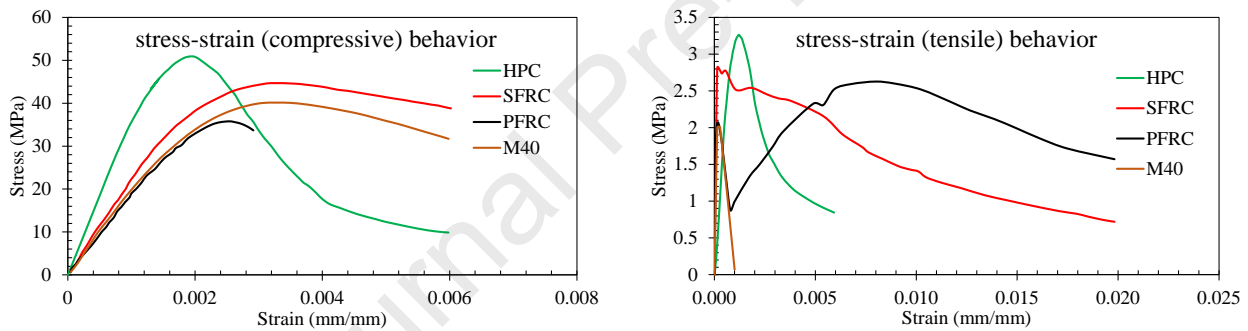


Fig. 2. Stress-strain relationship of different concrete material models

For stress-strain curves in the compressive behavior, PFRC has a smaller strain and peak stress compared to that of other materials. Additionally, HPC, SFRC, and M40 show a similar strain capacity in compression. Meanwhile, it is observed that there is a large difference in stress-strain curves for tensile behavior. M40 demonstrates the smallest tensile strain capacity, followed by HPC. SFRC and PFRC exhibit a very high tensile strain. Specifically, the PFRC material shows a distinct tensile behavior, at first the stress increases then later it decreases to close to half the peak then again increases. Moreover, it can be found that PFRC and M40 have a lower tensile stress compared to that of HPC and SFRC models.

Table 1. Mechanical properties of various concrete material models

Material	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)	Density (kg/m ³)
HPC	51.0	3.26	32,000	2,450
SFRC	44.7	2.80	22,058	2,360
PFRC	35.8	2.62	19,227	1,860
M40	40.2	2.00	20,134	2,350

2.2.2. Reinforcing bars and prestressing tendons

Reinforcing bars and prestressing tendons are modeled as bilinear isotropic materials. Both reinforcing bars and prestressing tendons are modeled according to the overall modeling method with bonded contact with concrete. Their mechanical properties are given in Table 2.

Table 2. Mechanical properties of reinforcing bars and prestressing tendons

Material	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)	Coefficient of thermal expansion (C ⁻¹)
Reinforcing bar				
Steel NL	400	600	200,000	-
Prestressing tendon				
Steel NL	1,670	1,860	195,000	1.2E-5

2.3. Application of prestressing forces on tendons

The prestressing force can be applied to a numerical model of a structure through the equivalent strain and stress or the lowering temperature methods. The lowering temperature method is employed in this study where the temperature of prestressing tendons are lowered to reflect the interaction force due to the prestressing action. In this process, the equivalent lowering temperature is calculated for the specific value of the prestressing force through the thermal contraction of tendons according to the following equation:

$$\Delta T = \frac{P}{E * A * \delta} \quad (1)$$

where ΔT is the lowering the temperature; P is the prestressing force; E is the elastic modulus of prestressing tendons; A is the cross-sectional area of a prestressing tendon; and δ is the coefficient of the thermal expansion of a prestressing tendon. In this study, the lowering temperature is calculated as -673°C . The temperature can be calculated by adopting different prestressing levels. In general, a prestressing force is considered to be 60 to 75% of the ultimate tensile strength of prestressing tendons. The prestressing force applied in this study is 70% of the ultimate tensile strength of a prestressing tendon.

2.4. Numerical model of RCB

A 3D FEM with continuum elements is commonly considered as one of the best modeling approaches of structures. In particular, 3D FEM with embedded reinforcing bars is a promising modeling technique for reinforced concrete structures. The cylindrical wall of RCB contains horizontal hoops and vertical reinforcing bars while the dome contains hoops and radial reinforcements. The numerical models of RCB are developed within the capability of ANSYS where the modeling process of the reinforced concrete portion and the addition of prestressing tendons are depicted in Figs. 3 and 4, respectively.

To construct 3D FEM without prestressing tendons as shown in Fig. 3, the *solid187* element is used for concrete, the *beam189* element is used for reinforcing bars, and the *conta175* is utilized to model the contact element between the concrete and reinforcements. The *solid187* element is a higher order 10-node solid element with a quadratic displacement behavior. There are three degrees of freedom, i.e., three translations in X, Y, and Z directions, at each node of this element. The *solid187* element has plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. The *Beam189* element is a quadratic 3-node 3D beam element, which contains six to seven degrees of freedom at each node, i.e., translations in the X, Y, and Z axes and rotations about these axes. This beam element includes elasticity, plasticity, creep, and nonlinear material models. Meanwhile, the *conta175* element represents the contact and sliding between a line and a surface in 2D or 3D. A contact occurs when the element surface penetrates one of the target elements on a specified target surface. Also, the *conta175* element can be applicable to simulate the delamination at the

interface. The model was meshed into 310,122 prism solid elements after conducting a mesh-convergence test. It is assumed that the base of the structure was fixed to the ground.

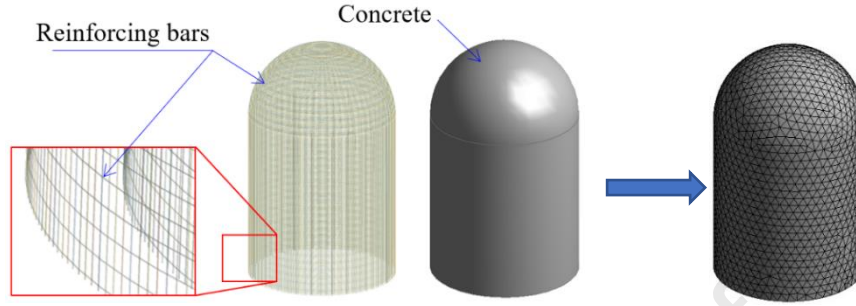


Fig. 3. A finite element modeling of RCB without prestressing tendons.

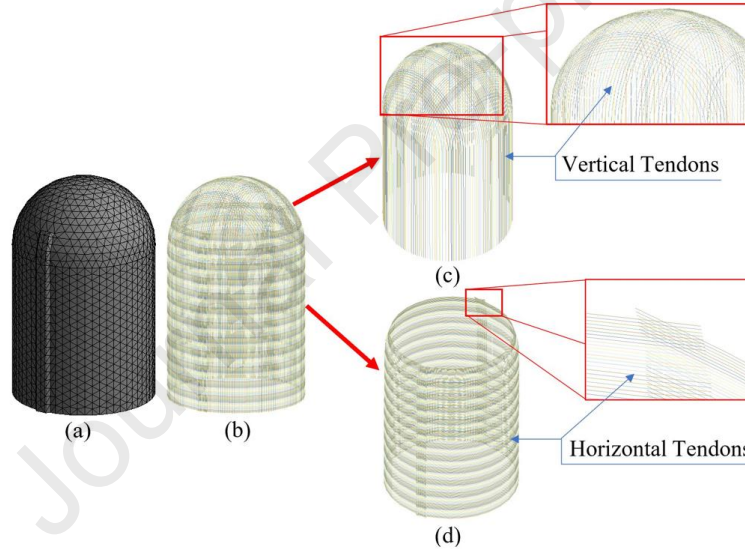


Fig. 4. A finite element modeling of RCB with prestressing tendons.

Finite elements of the prestressing tendons are added to FEM of the reinforced concrete RCB as shown in Fig. 4. In RCB, prestressing forces are applied separately for horizontal and vertical tendons. For horizontal tendons, each strand covers half of the cylindrical wall, so each tendon was anchored on the alternate buttress at 180 degrees' arrangement. These horizontal tendons are placed at 300 mm spacing, as shown in Fig. 4(d). Accordingly, a total of 165 and 30 tendons are arranged in the cylindrical wall and on the dome of RCB, respectively [44]. Meanwhile, 100 U-shaped vertical tendons are arranged in the spacing of 750 mm. Each tendon line with a cross-sectional area of $5,825 \text{ mm}^2$ consists of 42 seven-wire strands with a nominal diameter

of 15.2 mm. The tendon's arrangement details are also shown in Fig. 4. The prestressing tendons are modeled as bonded beam elements to the concrete. The *beam189* element is used to model prestressing tendons.

2.5. Eigenvalue analyses

Eigenvalue analyses for the FE models with and without prestressing tendons are performed to compare vibrational mode shapes and the corresponding frequencies. Figs. 5 and 6 show the selected mode shapes of the FE model without prestressing tendons and the one with prestressing tendons, respectively. It is observed that the 3rd and 4th modes of one model and the 5th and 6th modes of the other model are comparable. The first torsional mode of the model without a prestressing tendon is the 9th and it is comparable to the 7th mode of the model with prestressing tendons. The corresponding natural frequencies of the vibrational modes presented in Fig. 5 and Fig. 6 are listed in Table 3. The numerical model with prestressing tendons is approximately 3% stiffer than that without a prestressing tendon.

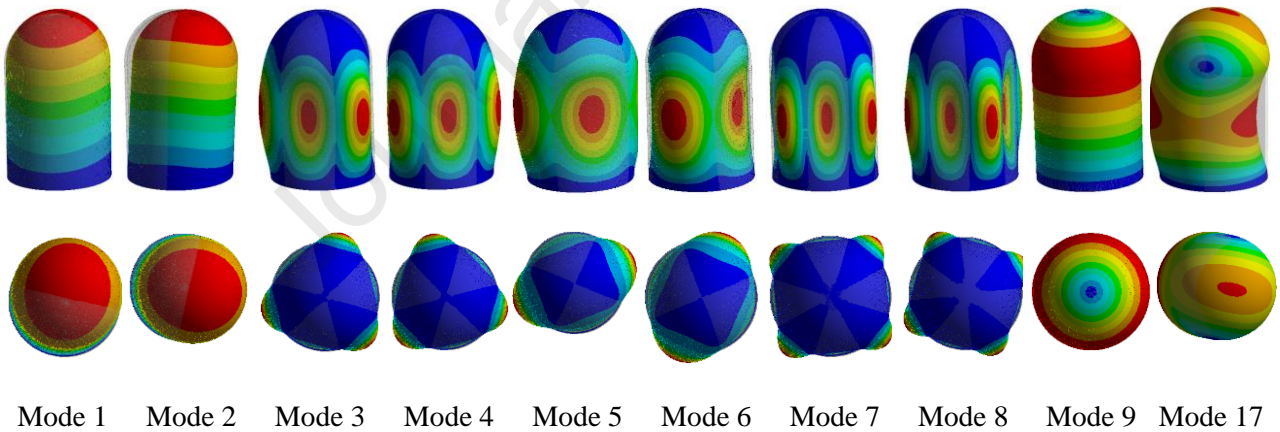


Fig. 5. Vibration mode shapes of the FEM without prestressing tendons

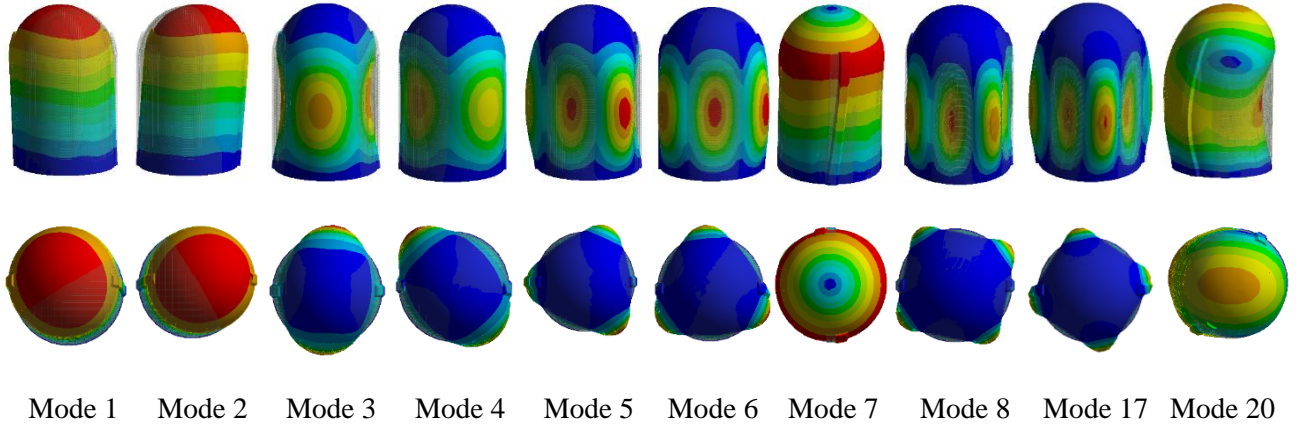


Fig. 6. Vibration mode shapes of the FEM with prestressing tendons

Table 3. Natural frequencies (Hz) of different numerical models of RCB

Mode	Non-prestressed model	Prestressed model
1	4.588	4.719
2	4.635	4.770
3	8.274	8.252
4	8.359	8.419
5	8.558	8.639
6	8.615	8.755
7	9.775	9.853
8	11.189	11.557
9 (17)	11.327	11.664
17 (20)	13.69	13.944

3. Seismic capacity evaluation of RCB

3.1. Pushover analyses

The base shear-deformation curve of a structure is commonly known as a capacity curve which can be obtained from a pushover analysis. Through the capacity curve, different cumulative damages of the structure can be identified. There are proposed definitions of damage states for shear walls in buildings [43] and nuclear facilities [44]. However, since RCB is a special structure combining a dome and a cylinder, it is different from other conventional RC wall structures. A specific guideline for defining damage states of such structure is not proposed yet. Therefore, damage states should be defined based on the capacity of the structure itself rather than adopting existing references, which were proposed for common plane shear walls. In this study, a

pushover analysis is performed to obtain the capacity curve and identify the cumulative damages of the structure.

The top lateral displacement is a critical response of RCB since it is a simple cantilever-type structure [17, 18, 45]. Pushover analyses are performed to determine the force-displacement relationships and the performance levels of the structural models. The applied load has an inverted-triangular shape as shown in Fig. 7(a). Fig. 7(b) presents the load-displacement relationship where the initiations of cracking, yielding, and crushing are indicated.

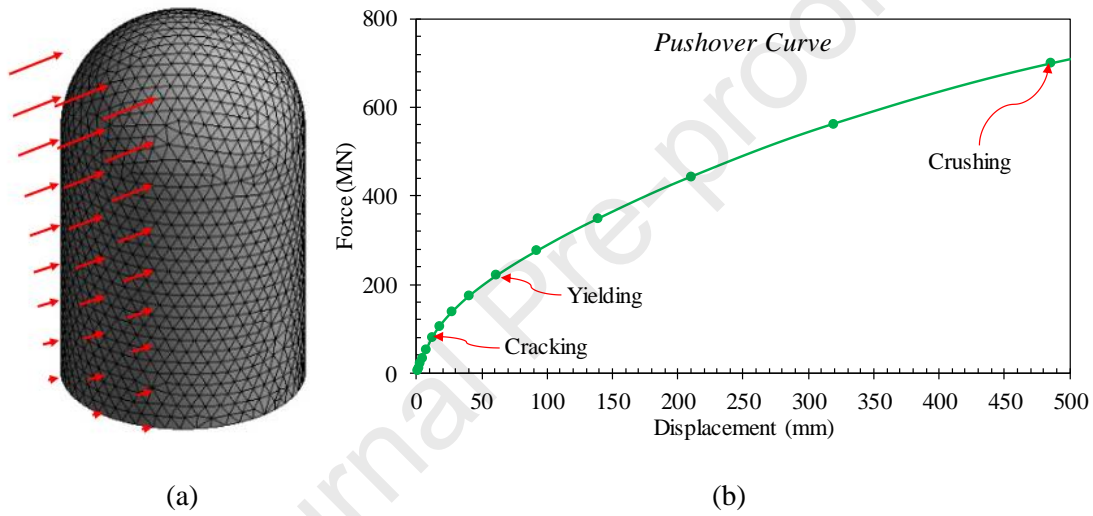


Fig. 7. Pushover analysis of RCB; (a) load distribution and (b) capacity curve.

3.2. Effect of various concrete material models

Pushover analyses are performed for each of the numerical models with a specific concrete material model. Four concrete material models presented in Fig. 2 were employed in numerical modelings of RCB with or without prestressing forces. Fig. 8 shows the base shear-displacement relationships of RCB with various concrete material models without prestressing forces. It is observed that the material models affect the capacity curves of RCB significantly. The nonlinear behavior starts at the top displacement of 10 mm for all concrete materials except for HPC, while for HPC, the nonlinear behavior starts at the top displacement of 15 mm. The structural capacity of RCB with the HPC model is the highest among the studied group and is followed by RCB with SFRC, PFRC, and M40 models. The strengths of RCB with HPC and SFRC models are 32.5% and

11.8% higher than that of the M40 model, respectively. RCB with the PFRC model does not improve the structural capacity in comparison with that using the M40 model. This is attributed to the reason that the used PFRC material contains a lower value of elastic modulus and compressive strength in comparison to all the other material models, as shown in Table 1. However, if we observe the performance of PFRC with a view that it is the weakest material model presented in this study, it is having almost similar seismic performance (less than 3% discrepancy) with M40. The distinct S_S curve for tensile behavior of PFRC can be the reason for PFRC giving comparable performance with M40. These results agree with previous studies [41, 42].

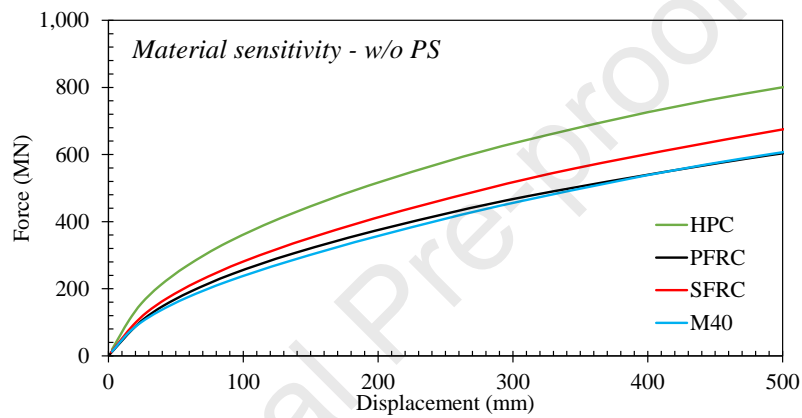


Fig. 8. Influence of various concrete material models

3.3. Effect of prestressing forces

Nonlinear static pushover analyses are performed for RCB models with and without prestressing forces to study effects of prestressing forces on the seismic capacity of RCB. Fig. 9 shows the capacity curves of RCB with and without prestressing forces where the M40 model is used for both numerical models. One can observe the significance of prestressing forces on the seismic capacity of RCB. The capacity curve of RCB with prestressing forces deviates from that without a prestressing force from around the start of nonlinearity of the curve. As the displacement increases, the discrepancy becomes larger.

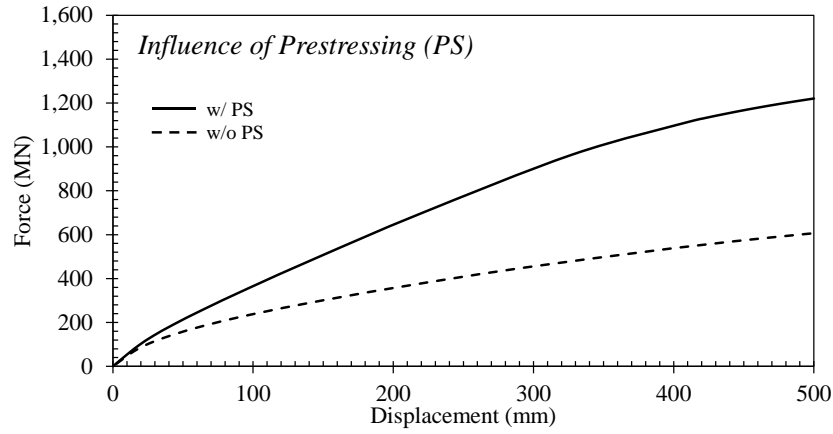


Fig. 9. Pushover curves of RCB with and without prestressing forces for the M40 concrete model.

Fig. 10 shows the capacity curves of RCB with different material models with and without prestressing forces. It is observed that strengths of RCB with prestressing forces for all concrete material models are 29-30% higher than those of RCB without prestressing forces at the initiation of the yielding. After the yielding, the difference of the strength increases to 43% to 48%.

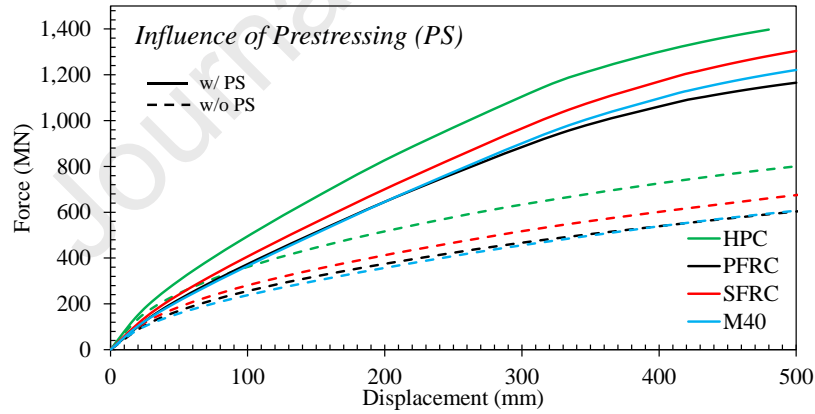


Fig. 10. Effects of prestressing forces for various concrete models

3.4. Proposed damage states

States of cumulative damage of RCB are monitored during pushover analyses and indicated in Fig. 11. Three proposed damage states are the initiation of the concrete cracking as a minor damage, the initiation of the rebar yielding as a moderate damage, and the initiation of the concrete crushing as an extensive damage. They are referred to as DS1, DS2, and DS3, respectively. This approach is also consistent with studies elsewhere [17,

46]. Table 5 presents the proposed damage states and corresponding damage indices for RCB with various concrete material models.

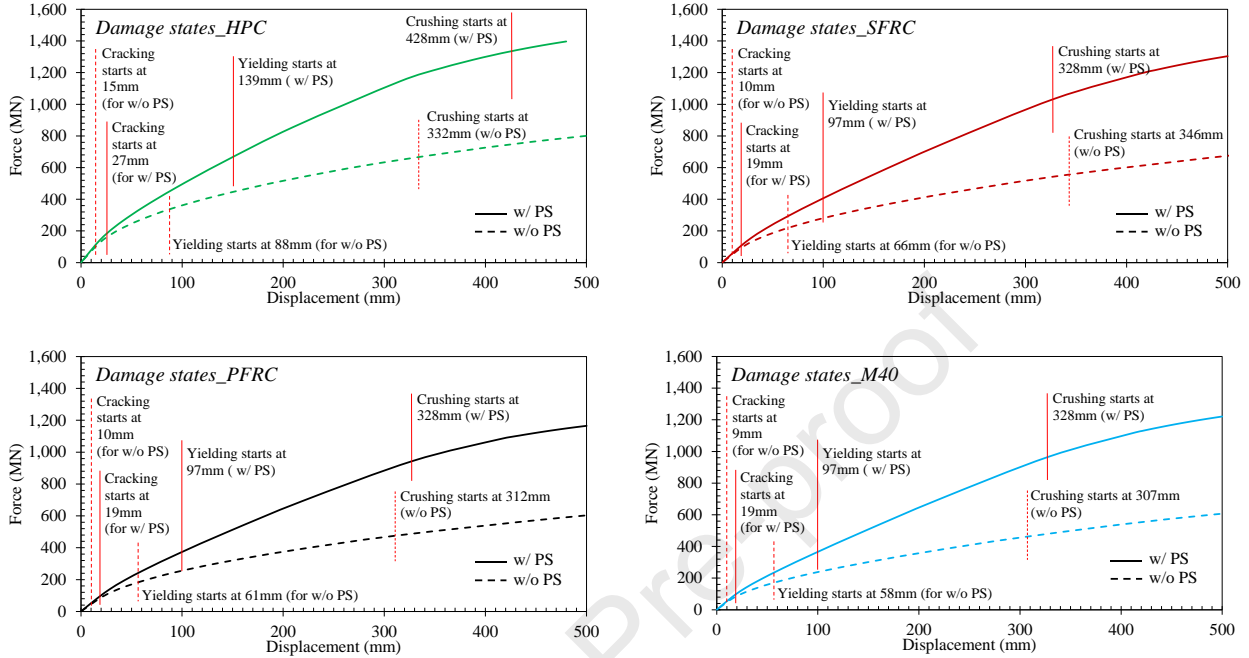


Fig. 11. Specified damage states for RCB structure

For all material models and all damage states, the strength capacity of the prestressed RCB is higher than that of non-prestressed RCB. The displacement capacity of the prestressed RCB is higher than that of the non-prestressed RCB for all combinations of material models and damage states, except for the case of SFRC-DS3 where the displacement capacity of the prestressed RCB is slightly lower than that of the non-prestressed RCB. One can notice that the displacement capacity of the prestressed RCB at DS3 is only slightly higher than that of the non-prestressed RCB, for cases of PFRC and M40. Introducing a prestressing force to a structure improves the strength capacity, but it does not necessarily improve the displacement capacity corresponding to the crushing damage state.

Table 5. Defined limit states of RCB based on pushover analyses

Concrete Model	Damage state	Base shear (MN)		Displ. (cm)		Drift (%)		Description
		w/o PS	w/ PS	w/o PS	w/ PS	w/o PS	w/ PS	

	DS1 (Minor)	107.38	194.85	1.55	2.75	0.02	0.04	Concrete cracking
HPC	DS2 (Moderate)	339.57	632.77	8.90	13.99	0.11	0.18	Rebar yielding
	DS3 (Extensive)	662.31	1338.78	33.27	42.85	0.43	0.55	Concrete crushing
	DS1 (Minor)	51.27	107.92	1.01	1.91	0.01	0.02	Concrete cracking
SFRC	DS2 (Moderate)	222.47	397.36	6.69	9.72	0.09	0.12	Rebar yielding
	DS3 (Extensive)	558.87	1034.01	34.63	32.83	0.44	0.42	Concrete crushing
	DS1 (Minor)	48.83	96.52	1.08	1.90	0.01	0.2	Concrete cracking
PFRC	DS2 (Moderate)	192.10	365.23	6.13	9.71	0.08	0.12	Rebar yielding
	DS3 (Extensive)	476.77	945.02	31.23	32.82	0.40	0.42	Concrete crushing
	DS1 (Minor)	44.38	98.49	0.94	1.90	0.01	0.02	Concrete cracking
M40	DS2 (Moderate)	174.08	357.40	5.81	9.71	0.07	0.12	Rebar yielding
	DS3 (Extensive)	461.86	966.53	30.71	32.82	0.39	0.42	Concrete crushing

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Fig. 12 presents the base shear at various damage states for different concrete models. RCB with the HPC model shows higher performance to withstand the lateral force due to the seismic load than RCBs with all other concrete material models. Base shears at DS1, DS2, and DS3 for RCB with the HPC model and without prestressing forces is 1.97, 1.77, and 1.38 times those of RCB with the M40 model without a prestressing force, respectively. For RCB with prestressing forces, base shears at DS1, DS2, and DS3 for the HPC model are 2.42, 1.95, and 1.43 times those of the M40 model. On the other hand, RCBs with SFRC, PFRC, and M40 models have comparable damage capacities for all three damage states.

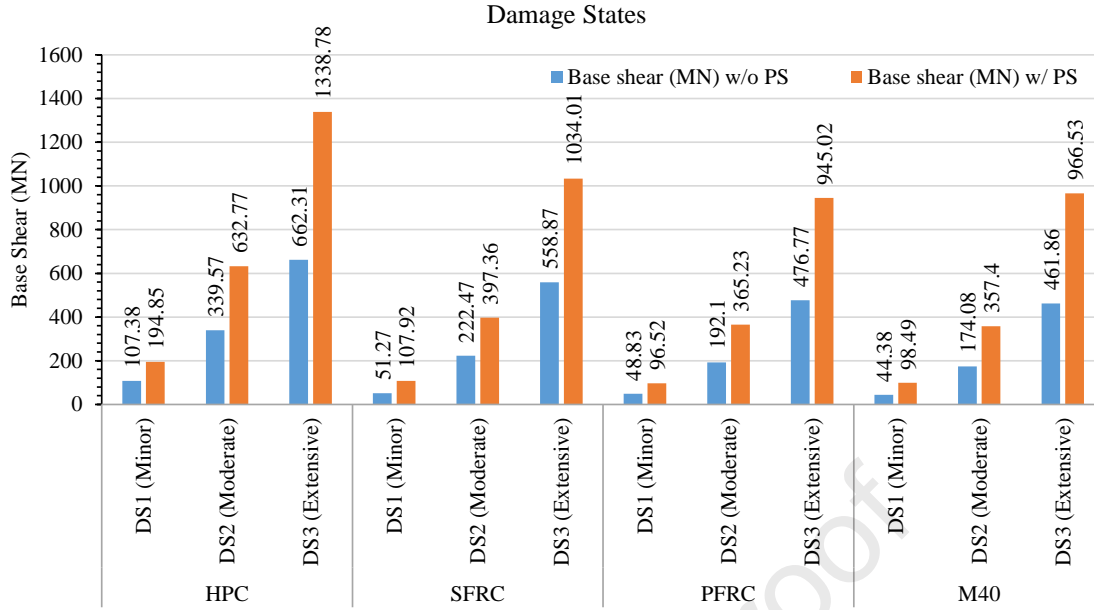


Fig. 12. Base shears at various DSs with respect to various concrete materials

To observe the effect of prestressing forces, the base shear at DS1 for RCB with the HPC model with prestressing forces is 1.82 times that for the same model without a prestressing force. For RCB with the SFRC model, this ratio, i.e. the base shear at DS1 of RCB with prestressing forces to that without a prestressing force, is 2.10, while for PFRC and M40, they are 1.97 and 2.20, respectively.

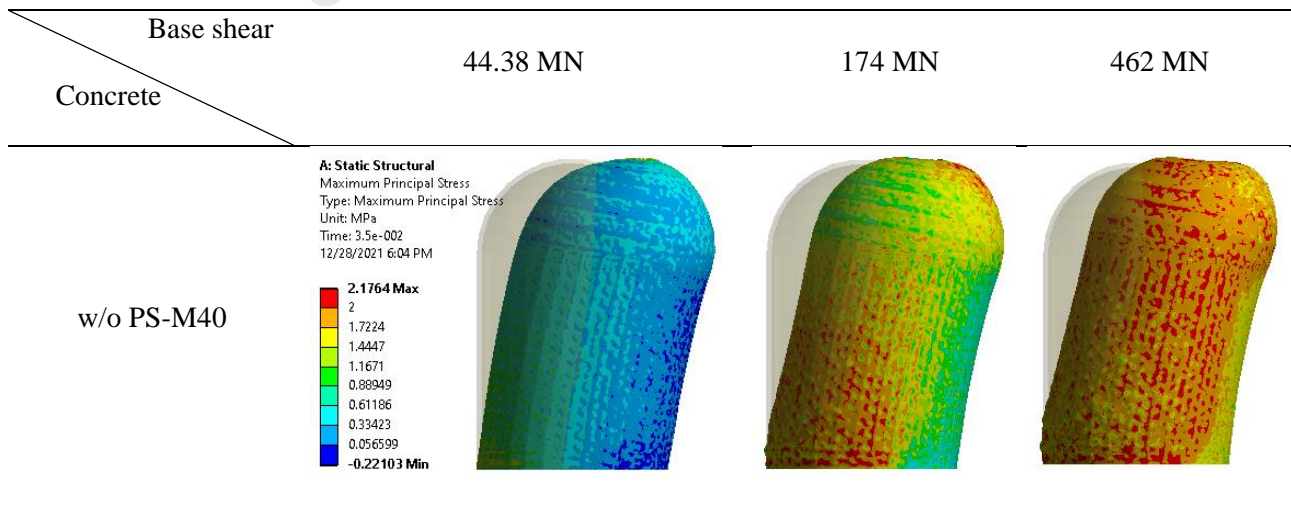
A similar pattern is observed for all models with and without prestressing forces at DS2 and DS3. At DS2, the aforementioned ratios for the HPC, SFRC, PFRC, and M40 models are 1.86, 1.78, 1.90, and 2.05, respectively. At DS3, the ratios for the HPC, SFRC, PFRC, and M40 models are 2.02, 1.85, 1.98, and 2.09, respectively. Therefore, the base shear capacity of RCB with prestressing forces is around two times that without a prestressing force, for all damage states and for all concrete models. This indicates that the consideration of prestressing forces in a numerical analysis of RCB is crucial for a reliable and accurate assessment of the seismic performance.

To investigate the effect of material properties and the effect of prestressing forces on local responses of RCB, the maximum principal stresses are monitored. Table 6 shows the maximum principal stress distributions at specific load levels for RCBs with different material models. The base shear capacities of RCB with the M40 model without a prestressing force are taken as the reference load levels, i.e. 44.38 MN, 174

MN, and 462 MN for DS1, DS2, and DS3, respectively. The first row of Table 6 shows the maximum principal stress distribution of RCB with the M40 model without prestressing forces at different damage states. It is observed that cracks occurs when the tensile stress in concrete reaches 2.0 MPa, then cracks propagate from just above the support towards the cylindrical part of RCB. At the initiation of the yielding (DS2), cracks are observed at the dome, too. Finally, at DS3, cracks are extensively spread to RCB.

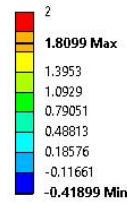
From the second row to the fifth, the maximum principal stress distributions of RCB with the M40, PFRC, SFRC, and HPC models with prestressing forces are presented, respectively. It should be noted that cracks occurred if the tensile stress of concrete reached 2.62 MPa, 2.80 MPa, and 3.26 MPa for PFRC, SFRC, and HPC materials, respectively. The distributions are captured at the reference load levels. The pattern of the crack propagation is similar for all RCB with different material models. However, the level of the crack distribution is different for different material models. For a same load level, RCB with the HPC model is the least damaged. At the 44.38 MN base shear level, no crack is observed from any of the RCB models with prestressing forces. At the 174 MN base shear level, cracks are observed in a very limited area of RCB with the M40 model, while no crack is observed in RCB with the other concrete models. These results demonstrate a significant reduction in concrete cracking and rebar yielding in the HPC model, followed by the SFRC and PFRC models in comparison to the M40 model.

Table 6. Evolution of the principal stresses of RCB at different base shears



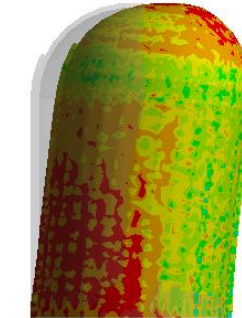
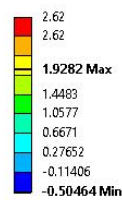
w/ PS-M40

B: Static Structural
 Maximum Principal Stress
 Type: Maximum Principal Stress
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 Time: 4.928571e-002
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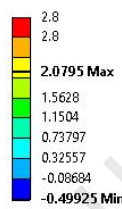
w/ PS-PFRC

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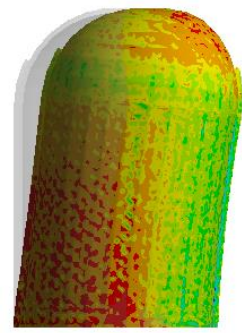
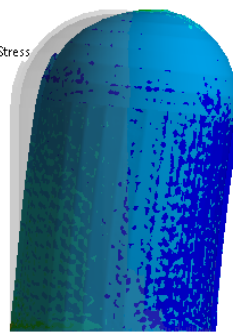
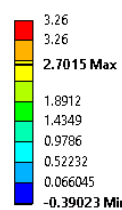
w/ PS-SFRC

B: Static Structural
 Maximum Principal Stress
 Type: Maximum Principal Stress
 Unit: MPa
 Time: 4.658385e-002
 12/27/2021 8:53 PM



w/ PS-HPC

B: Static Structural
 Maximum Principal Stress
 Type: Maximum Principal Stress
 Unit: MPa
 Time: 2.318393e-002
 12/27/2021 9:19 PM



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303

4. Conclusions

304 This study evaluates the seismic capacity of RCB accounting for the effects of various concrete materials,
 305 namely, PFRC, SFRC, and HPC, and prestressing forces. A nonlinear 3D FEM of RCB is developed using
 306 ANSYS, a commercial software, and a series of pushover analyses are performed. A parametric study is then

conducted considering various concrete materials and prestressing forces. The following conclusions are drawn based on numerical analyses.

- HPC improves the strength capacity of RCB significantly, while SFRC improves it moderately, in comparison to a normal concrete.
- Prestressing forces improve the seismic capacity of RCB significantly in comparison to that of a non-prestressed RCB as the strength is improved up to 30% at the initiation of yielding, for all concrete material models considered in this study. It convinces us that the consideration of prestressing forces is necessary in a numerical analysis of RCB, which is neglected in many previous studies.
- The base shear capacity of RCB with prestressing forces at each of the three damage states is around twice that of RCB without prestressing forces for all material models.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Author's contributions statement

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Conceptualization: B.T.; Methodology: B.T.; Software and FEM model: B.T.; Formal analysis, B.T.; Investigation, B.T.; Writing—original draft preparation, B.T.; Writing—review and editing of the original draft: B.T., D.D.N.; Writing—review and editing of the first draft: B.T., D.D.N., M.S.A., T.H.L. Writing—review and editing of the final draft: B.T., D.D.N., M.S.A., T.H.L. Project administration: T.H.L.; Supervision: T.H.L.; Funding acquisition, T.H.L. All authors have read and agreed to the published version of the manuscript.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.