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Finite Element Parametric Studies on Buckling Restrained Brace

P. S. Shete[1*], S. N. Madhekar[2], A.F.Ghowsi[3]

[1] Department of Civil Engineering, Research Scholar, College of Engineering Pune, Pune 411 005, India
[2]Department of Civil Engineering, Professor, College of Engineering Pune, Pune 411 005, India
[3]Department of Civil Engineering, Post-Doctoral Research Fellow, Indian Institute of Technology Delhi, New Delhi 110 016, India

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Abstract

Concentric Braced Frame (CBF) is an efficient lateral load resisting system. It adds stiffness and strength to the structural system. However, the repeated failures of concentric braces in the past earthquakes has raised concern of its overall seismic performance and ultimate deformation capacity. Buckling Restrained Brace (BRB) is becoming popular energy dissipation device in the field of seismic resistant steel structures. BRB absorbs substantial amount of energy during cyclic performance. By preventing the buckling of the brace, a symmetric and stable hysteresis curve of BRB is achieved, as it dissipates high amount of energy in every single cycle. In the present research work, numerical modelling, and prediction of cyclic response of concrete BRB is presented. The numerical model is validated by comparing the results with the previous experimental work. Numerical simulations have been performed using the finite element software ABAQUS. The yielding core length is varied from 1m to 3 m, and the coefficient of friction is varied from 0 to 1. The parametric study is carried out to investigate the influence of yielding core length and coefficient of friction on the hysteretic performance of concrete BRB. The performance of all the numerical models is accessed by comparing their hysteretic response and the compression adjustment factor. With increasing the friction coefficient between the steel core and the concrete, an unsymmetrical hysteretic response is observed, with reduction in energy dissipation. Axial stiffness of short length BRB is found to be higher, as compared to the longer length. From the parametric study, it is revealed that the length of the yielding core and friction impact the cyclic response of BRBs.

Keywords: Buckling Restrained Brace (BRB), Seismic performance, Finite Element Analysis, Hysteresis behaviour, Core length, Friction coefficient.

1. Introduction

Buckling Restrained Braces (BRBs) are considered as one of the most efficient lateral force resisting energy dissipation devices. BRB uses the ductility of steel more effectively than the conventional concentric braces. In conventional concentric braces, the element offers lateral stiffness; however, braces are expected to yield in tension and buckle in compression. When buckling occurs, the brace member loses its stiffness, part of load carrying capacity, and has lowered energy absorbing capability. BRBs overcome this buckling problem because of its equivalent load carrying capacity in tension and compression. In the present research work, numerical modelling, and prediction of cyclic response of concrete BRB is presented. The numerical model is validated by comparing the results with the previous experimental work. The validated model is used to investigate the influence of length of yielding core and type of unbonding material (i.e. coefficient of friction).

The first two BRB specimens were tested by Yoshino in 1971 [1] under cyclic loading. Both specimens consisted of steel plate and reinforced concrete panel casing. The specimen with debonded steel plate, and without debonded steel plate were experimentally tested. The specimen with debonded steel plate showed efficient energy absorbing and deformation capacity. Wakabayashi in 1973 [2] further specified that the debonding steel plate from the concrete casing provides more ductility capacity. Till date, considerable research work on the development of BRB has been carried out in Japan, US, and Asia.[Previous experimental studies on BRB reveal the high energy dissipation capacity, by means of stable and symmetric hysteresis loops under cyclic loading [3-5]. To characterize hysteretic response of BRB, component testing was done [6]. The influence of the strength and stiffness of external restraining member, core length, width-to-thickness ratio, and thickness of core member on the BRB performance, was researched [7]. Extensive numerical study has been conducted to verify potential of BRBs to improve the seismic response.[8-9]

The length of BRB core has substantial effect on its overall behaviour. The moderate length BRB can efficiently dissipate energy [10]. Friction between the core and the restraining member of BRB may lead to larger compression overstrength

*Corresponding author. Tel: +918446495616; E-mail address: sheteprajakta.s@gmail.com

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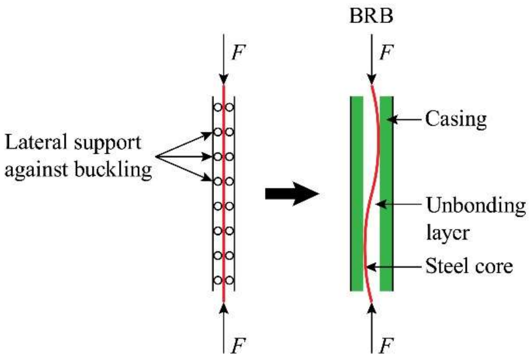


Fig.1.Components of BRB

and result in global flexural buckling of outer core [11]. Hence, the study of length and the friction coefficient of BRB is essential. In the present research work, numerical modelling, and prediction of cyclic response of concrete BRB is presented. The parametric study is carried out to investigate the influence of yielding core and coefficient of friction on the hysteretic performance of concrete BRB.

BRB is displacement-dependent energy dissipation device which dissipates energy while yielding. BRB has three major components; steel core, bond-preventing layer and casing. Figure 1 shows the components of BRB. The BRB along its length is divided as middle yielding part and non-yielding rigid parts at both ends. The increased cross-section of the non-yielding part ensures that it remains elastic and thus plasticity is concentrated in the middle part of the steel core. The bond-preventing layer decouples the casing from the core. A variety of cross-sectional shapes, such as flat plate, cruciform can be used for yielding steel core. The cross-sectional area of BRB core can be significantly lower than that of the conventional braces, as its performance is not limited by buckling criteria. To avoid excessive strain in BRB, which may lead to core fracture, the yielding core length must be selected judiciously. Concrete-filled casing provides the stiffness to restrain the member from buckling [12-13]. Clearance (gap) between the steel core and the restrainers is provided to accommodate the Poisson expansion of the steel core in compression. The gap also prevents the restraining mechanism from carrying the axial force at large deformation in tension and in compression.

2. Analytical Study

Finite element analysis of BRB models has been carried out using commercial software ABAQUS 6.13. Investigation of the influence of yielding core and coefficient of friction on the hysteretic performance of concrete BRB has been carried out keeping the cross-section of the steel core constant. The details of finite element modeling, loading history and results are discussed in the following sections.

2.1 *Finite Element Modeling and validation of analytical model*

Eight node first order hexahedral (C3D8R) element with reduced integration technique and Hourglass control are used to model the brace in ABAQUS. The behaviour of BRB under cyclic loading condition is modeled using damage plasticity model, which includes the nonlinear isotropic and kinematic hardening behaviour. Elastoplastic material properties with combined isotropic and kinematic hardening behaviour are applied to model the steel core element. All other casing portion is modeled as perfectly elastic. Validation of ABAQUS model is done with the previous experimental work [14]. The same material model is assumed for the present work and the values are specified in Table 1.

For steel core and outer steel tube Young's Modulus is 210 GPa and Poisson's ratio is 0.3; whereas for concrete encasement, Young's Modulus is 21 GPa and Poisson's ratio is 0.18. General contact all with self-effect has been modelled as surface contacts to define the surfaces for steel core and the concrete, and the tangential behaviour is used for the penalty friction formulation to achieve different friction coefficients with hard contact for normal behaviour. The fine meshing pattern is adopted for yielding steel core and the coarser meshing for the remaining element. To obtain the mode shape, buckling analysis is performed initially on the brace with linear perturbation. For all braces L/1000 initial perturbation is assumed, where 'L' is the length of brace. Figure 2 shows the finite element model of BRB.

To account for the effect of loading direction on inelastic cyclic behaviour of material, the combined isotropic and kinematic hardening model has been considered. Kinematic hardening represents the yield surface translation in stress space through back stress α. The change in size of the yielding surface is described through isotropic hardening. Back stress represents the constant kinematic shift of the yield surface and is useful to model the effect of residual stresses. The kinematic hardening component $\dot{\alpha}$ is expressed as the combination of linear kinematic term and a nonlinear relaxation term [15].

Table -1. Calibrated kinematic hardening parameters of Steel core

σy (MPa)	C (MPa)	25000	21000	5950	935	300
235	γ	500	375	120	25	0

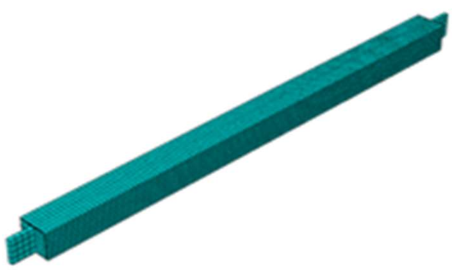
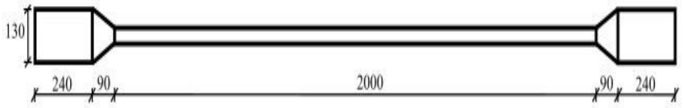
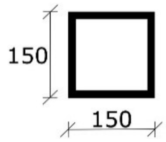


Fig. 2. Finite element model of BRB



(a)



(b)

Fig. 3. Details of BRB (a) core part; (b) steel casing

$$\dot{\alpha} = C\frac{1}{\sigma^0}(\sigma - \alpha)\dot{\bar{\varepsilon}}^p - \gamma\alpha\dot{\bar{\varepsilon}}^p \quad (1)$$

In Equation (1), C represents the initial kinematic hardening modulus, initial stress is given by σ^0, $\dot{\bar{\varepsilon}}^p$ signifies the equivalent plastic strain rate, γ defines the rate at which the kinematic hardening modulus decreases with increasing plastic deformation.

In the present study, the core steel of BRB is having yielding length of 2000 mm, thickness 20 mm and cross-sectional area 800 mm^2. Figure 3 shows the details of BRB used in the present study. Gap of 2mm is provided around the steel core and the concrete encasement. This gap caters the Poisson's expansion of steel core. Steel casing has thickness of 6 mm. The concrete encasement is provided between the steel core and the steel casing.

Analytical model used for the parametric study is validated with the previous experimental work conducted by [14]. The material properties, section dimensions and loading protocol are kept exactly the same as those used in the previous experimental work. Figure 4 shows the comparison of hysteretic behaviour of numerical model of the present study and the experimental work [14]. The predicted hysteretic response matches very well with the experimental study. Some minor variation in the hysteresis response is observed during latter stages between the numerical and experimental results. However, the main characteristics of the tested BRB, like the initial elastic stiffness, strain hardening behaviour of each cycle of loading and unloading, peak axial load values, are in perfect agreement with the numerical results. This validated model is used further for parametric study, to investigate the influence of yielding core and coefficient of friction.

2.2 Loading Protocol

To observe the cyclic loading performance of BRB, the previously used loading protocol is followed [14]. Figure 5 shows the loading protocol used for the present study. represents the gradually increasing symmetrical displacement till a maximum core strain of 2.5%.

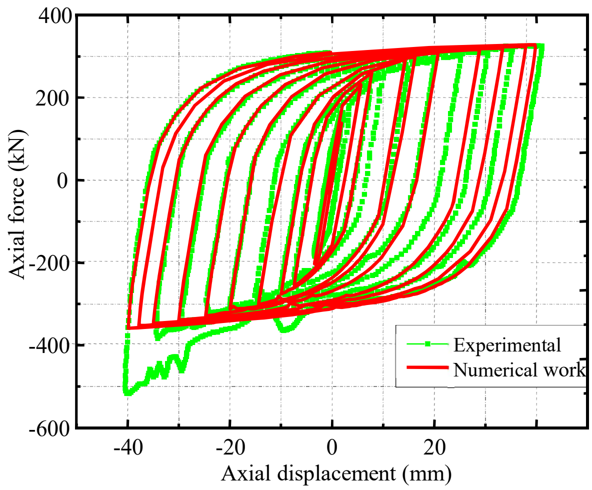


Fig.4. Comparison of hysteresis response

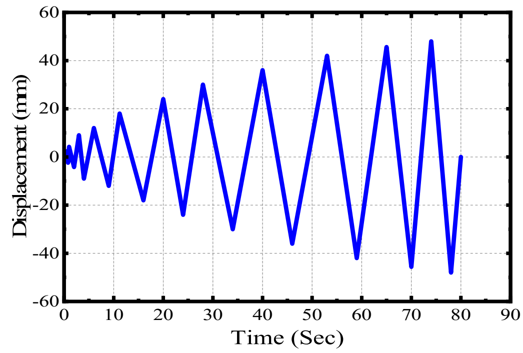


Fig.5. Loading protocol used for present study

3. Results and Discussion

A parametric study has been conducted to investigate the influence of length of yielding core and friction coefficient between the core and the buckling restraining part. The validated model is used to observe the overall cyclic behaviour of concrete BRB. The yielding core length is varied from 1 m to 3 m, and the coefficient of friction (μ) values are varied from 0 to 1. The lower value of friction denotes the greasy interface and the higher friction coefficient denotes the glued surfaces.

3.1 *Effect of Friction*

Figure 6 shows the hysteretic response of concrete BRB with varying friction coefficient values for 1m length. When a BRB is subjected to compression, due to Poisson's effect the lateral expansion of the steel core occurs. Because of the Poisson's expansion and friction between the core and the restraining mechanism, compression capacity of BRB is slightly more than the tension capacity. Cyclic behaviour and strain hardening of BRB is evaluated with the compression strength factor β and strain hardening factor ω. Table 2 presents the compression strength factor β and strain hardening factor ω for all the models. The compression strength adjustment factor β, is calculated as the ratio of maximum compression force to the maximum tension force in BRB. It has been observed that the compressive strength of

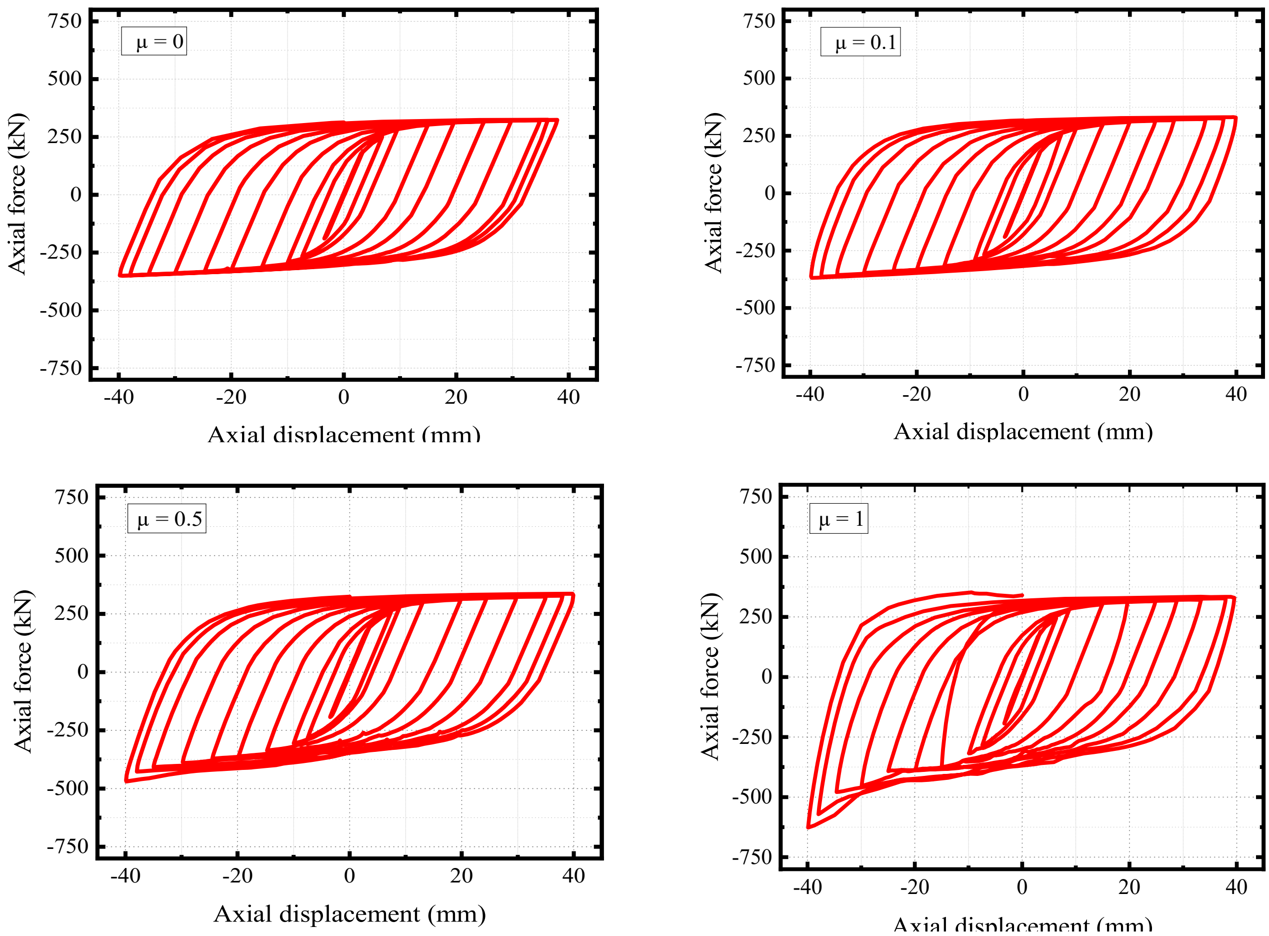


Fig.6. Hysteretic response of 1m length BRB

Table -2. Compression strength factor and strain hardening factor

Length of BRB (m)	Coefficient of friction (μ)	Max Compression Force (KN)	Max Tension Force (KN)	β	ω
1	0	350.33	324.25	1.08	1.72
1	0.1	368.97	331.61	1.11	1.76
1	0.15	392.37	334.92	1.17	1.78
1	0.5	469.22	336.54	1.39	1.79
1	1	626.69	352.37	1.78	1.87
2	0	347.31	330.41	1.05	1.76
2	0.1	358.72	328.19	1.09	1.75
2	0.15	373.14	332.59	1.12	1.77
2	0.5	435.93	336.98	1.29	1.79
2	1	801.09	414.66	1.93	2.2
3	0	242.17	257.06	0.94	1.37
3	0.1	358.06	327.87	1.09	1.74
3	0.15	285.06	273.33	1.04	1.45
3	0.5	254.89	238.82	1.06	1.27
3	1	375.62	299.94	1.25	1.60

BRB changes with the change in friction. The β value increases with the increase in coefficient of friction. As per AISC seismic provision, the value of β should be less than 1.3. The strain hardening factor ω is the ratio of maximum tension force in BRB to the yield force P_{ysc}. The yield force P_{ysc} is given by (2),

$$P_{ysc} = F_{ysc} A_{sc} \tag{2}$$

where F_{ysc} is the yield stress of the yield core, 235 MPa and A_{sc} is net area of the core. The calculated values of compression strength adjustment factor β for all the models are well in good agreement with AISC provision, except for the 1m length BRB with coefficient of friction 0.5 and 1, the values are greater than specified. Figure 7 and 8 show the hysteretic response of concrete BRB with varying friction coefficient values for the length 2m and 3m, respectively. Stable and approximately symmetrical hysteretic response of BRBs is observed for 1m and 2m length, except for coefficient of friction value 1, where, it has been observed that the compression resistance strength of BRB is increased

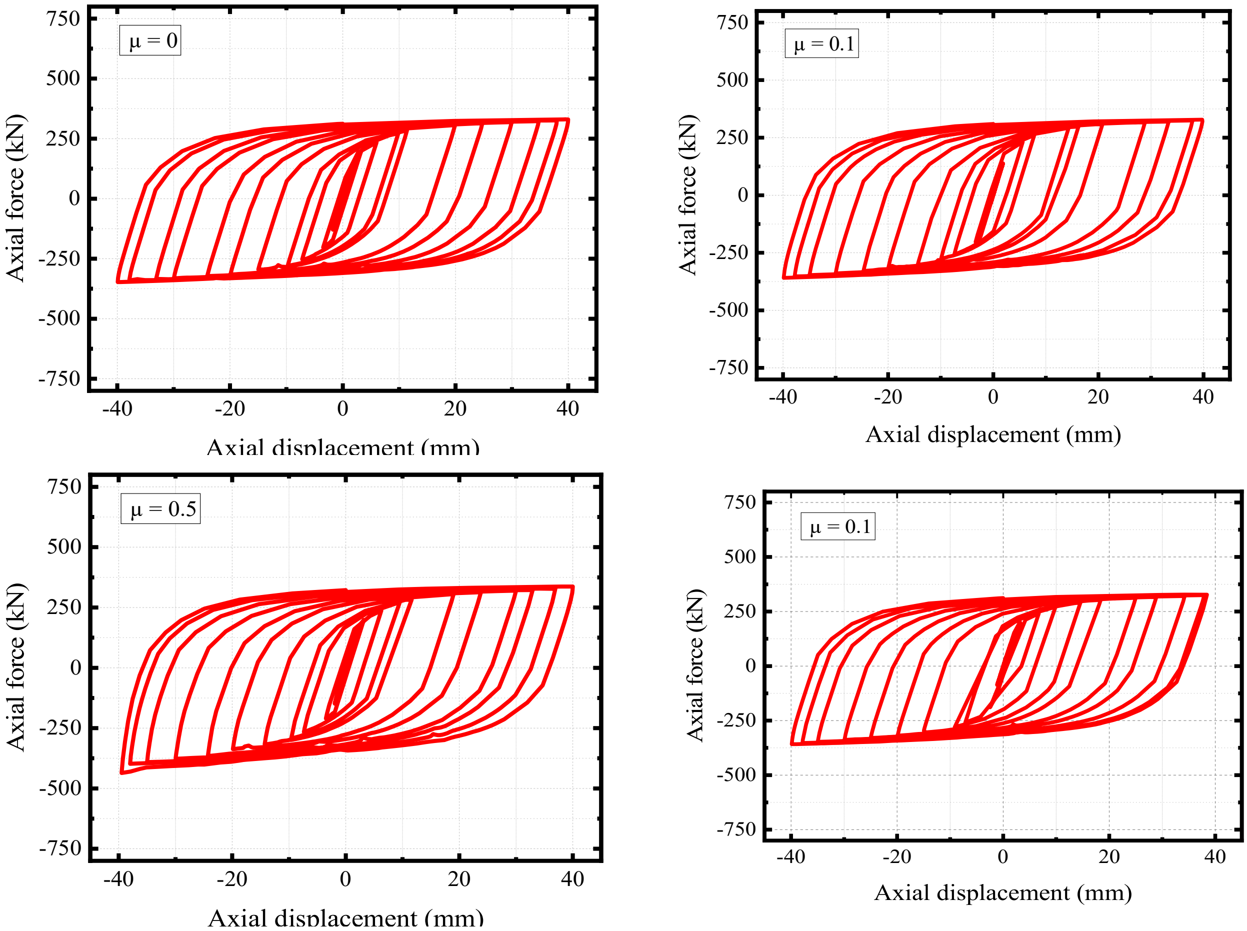


Fig.7. Hysteretic response of 2m length BRB

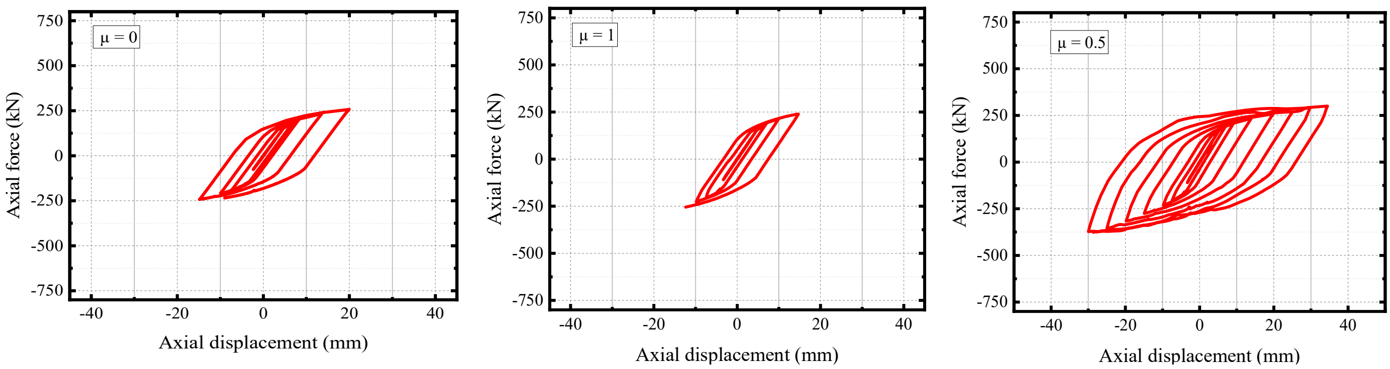


Fig.8. Hysteretic response of 3m length BRB

3.2 *Effect of Yielding Core Length*

To study the effect of yielding core length on hysteretic performance of concrete BRB, three length BRBs viz. 1m, 2m and 3m are considered. Figure 9 shows the comparison of hysteretic performance of three different yielding core length BRBs with same coefficient of friction value 0.15. It has been observed that BRBs with shorter yielding core length show stable hysteresis cyclic response behaviour. The BRBs with longer yielding core length could not be able to sustain all loading cycles. The degrading hysteresis response has been observed for the BRBs with longer yielding core length.

Figure 10 shows the comparison of the backbone curves and cumulative energy dissipation behaviour of BRBs with varying yielding core length. It has been observed that the BRBs with longer yielding core length possess lower axial stiffness as well as compression strength factor β, when compared with the shorter yielding core length. Cumulative energy dissipation has been observed similar for 1m and 2m yielding length BRB. From the present study, it has been observed that the yielding core length plays a vital role in cyclic performance of BRB. Selection of BRB core should be done carefully and the study of interaction between the core length and the coefficient of friction is essential.

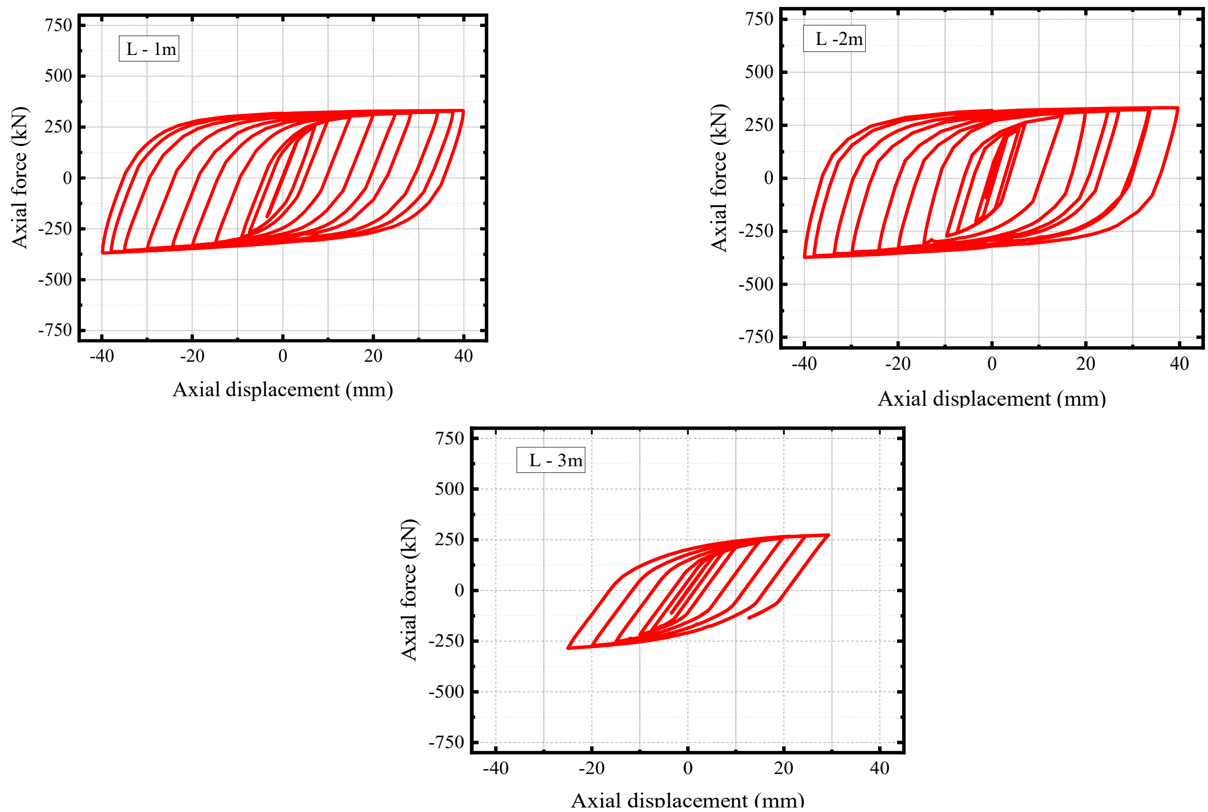
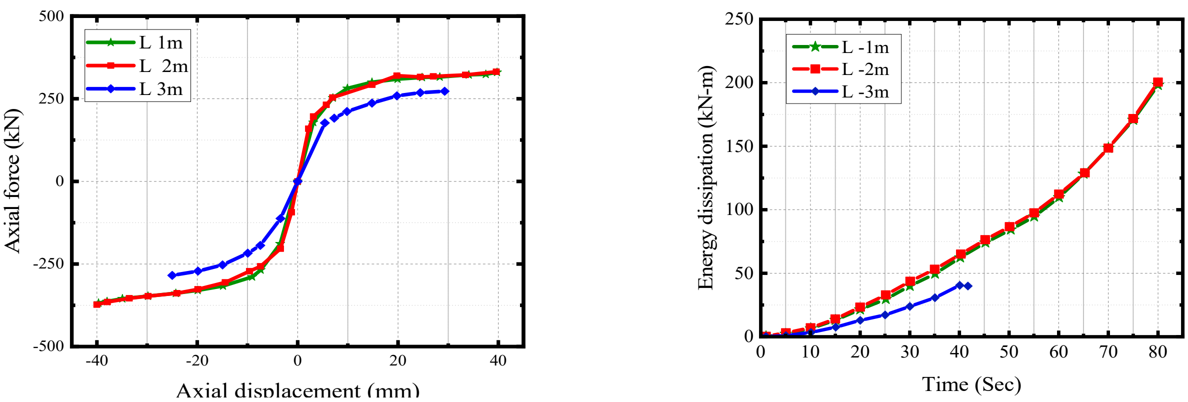


Fig.9. Hysteretic response of BRB with varying core length



(a) (b)

Fig.10. Comparison of a) Back-bone curves, b) Cumulative energy dissipation

4. Conclusions

In the present study, the numerical simulations have been performed using the finite element software ABAQUS. The parametric study is carried out to investigate the influence of coefficient of friction and yielding core length on the hysteretic performance of concrete BRB. The numerical model is validated by comparing the results with the previous experimental work. The same validated model is used for further parametric study and it is concluded that the BRB with coefficient of friction value between 0.1 to 0.2 gives the stable hysteresis response. For higher friction values of 1, the hysteresis response becomes unsymmetrical. As the coefficient of friction increases the compression strength factor β also increases. The yielding core length of BRB plays a vital role in the cyclic response behaviour. BRBs with longer yield length show the degraded hysteretic response as compared to BRB with shorter yield length. Higher axial stiffness is observed for the BRB with short yield length as compared to the longer length.

Disclosures

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