Development of an Alternative BRB Under the Compression Stage Using Light Gauge Square Steel Pipe and Mortar as Infill

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Abstract: Earthquakes frequently occur in the Philippines and there is a possibility of risk for most structures to sustain a great deal of damage especially for small and low-rise buildings. Buckling Restrained Braces (BRB) are usually used to help withstand strong seismic movements. However, the standard ones available are big, expensive, and intended for high-rise and big structures. A design for small scale BRB to be used for low-rise buildings and smaller structures is not yet available. This study aims to provide a development of a design prototype using locally available materials as a proposed alternative to the standard BRB used in construction. Using light gage square steel pipe and mortar, the research aims to propose an Alternative BRB (ABRB) design which will have sufficient compressive strength in serving its function. The research makes use of specimens made of steel pipes filled with mortar of various consistency (water to cement ratio) and compaction (number of tamps) to determine their effects to the compression strength of specimens. The proposed ABRB which produced the greatest strength was found to be the specimen with 0.7 water to cement ratio tamped 150 times. This specimen exhibited an increase in strength which is 2.41 times that of the hollow specimen. This indicated that the specimen with the lower water to cement ratio and the higher number of tamps tends to produce higher compressive strength. However, although the strength increase is high, the proposed ABRB specimens still failed in buckling at higher range. However, the proposed ABRB may still be considered to have partially restrained the buckling. Hence further enhancement should be made so that the ABRB can reach their yielding strength before buckling occurs.

Key Words: consistency; compaction; compressive strength; void ratio; W/C

1. INTRODUCTION

The Philippines is geographically located on the Pacific ring of fire which makes it prone to earthquakes. These earthquakes cause horizontal seismic movement that may damage structures. Throughout the years, the country has experienced numerous earthquake occurrences. Some famous ones are the 1990 Luzon Earthquake which collapsed 28 buildings in Baguio, the 2012 Negros Oriental Earthquake where the damage dealt to infrastructures were calamitous, and the 2013 Bohol Earthquake where around 14,500 houses were destroyed as well as some 73,000 more were damaged (Limos, 2019). Therefore, it is necessary for buildings to have proper retrofitting that can sustain seismic loadings. The use of braces such as buckling restrained braces (BRB) on structures is known to dramatically increase their strength against lateral loadings such as earthquakes. A BRB is a composite member that has a core member wrapped around a buckling cover that deals with axial forces to prevent buckling. The application of this kind of structural component is highly used for seismic design (Robinson, 2009). These BRB have been widely used in tall buildings that are in areas wherein seismic activities often happen (Watanabe, 2018). However, BRB are only fabricated currently for high rise structures in the country which means that there are no available BRB for low rise structures in the local market. An option to utilize BRB for low rise structures is to fabricate a smaller scale of BRB using the same concept of producing a composite member but only composed of steel and mortar. However, there is currently no standard in designing a smaller scale BRB. This is what the study planned to address.

The study aims to test the feasibility of an alternative BRB (ABRB) through compression test using readily available local materials such as light gauge steel and mortar. The proposed ABRB specimens with mortar of varying water to cement ratio (W/C) and varying compaction through the number of tamps applied were tested to determine the effect of consistency and compaction of mortar on their compressive strength. The study also aims to find the optimal combination of consistency and compaction to produce the highest increase in strength for the proposed ABRB when compared to hollow steel pipe specimens. The specimens were only tested for compression load, and their tensile capacity will not yet be considered in this study. The performance of these proposed ABRB specimens in the structures will also not yet be covered in the study.

2. METHODOLOGY

This research was started with the procurement of the galvanized iron square hollow pipes ensuring that they are readily available in the Philippine market. They were obtained from a local supplier in Bulacan, Pampanga. The cross-section of the square hollow pipe is 50mm x 50mm x 1.2mm in thickness. For the preparation of specimens, the first step was cutting the pipes to the designated lengths and sealing one end of the hollow steel pipes by welding a thin steel plate with a small hole so that air will be able to escape when mortar is poured inside. Four different pipe lengths (1.5-m, 2.0-m, 2.5-m, and 3.0-m), in combination with three W/C (0.7, 0.8, and 0.9), and three compactions (0, 75, 150 tamps) were adopted to prepare the specimens. The production of these specimens was carried out by filling the hollow pipes with mortars. Then, they were subjected to different compaction by the number of tamps applied. The specimens were weighed afterwards to determine the percentage void in each specimen.

In the mix design of the mortar, all materials were proportioned by weight. The cement to sand ratio was 1:3. The cement and the sand were dry mixed in small batches. Afterwards, water was added according to the W/C. The mortar mix was made in small batches to ensure uniformity. After which, the mortar was poured into the hollow pipe in 3 layers. The pipe was correspondingly applied with the designated tamps for each specimen, either 0, 75 or 150 tamps. The tamps were equally divided in each layer. The researchers used a rubber mallet in tamping the specimens on their side at height intervals of one-third the total height of specimens. Together with these specimens, mortar cylindrical samples with dimensions 4 inches in diameter and 8 inches in height were prepared to determine the compressive strength of mortar.

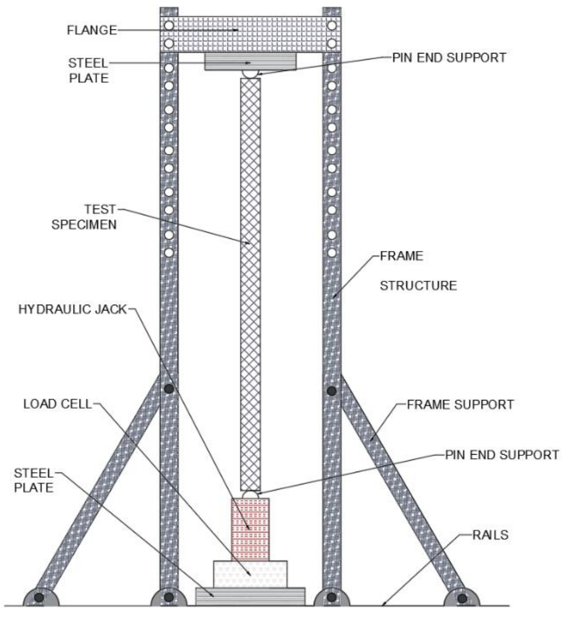


Fig. 1. Compression test setup using a loading frame.

The ABRB specimens were tested by using a hydraulic jack and a loading frame as shown in Figure 1. The specimens were required to have a curing of at least 28 days to reach the target strength. In fact, due to the lockdown brought by the COVID-19 pandemic, all specimens reached a curing age of 150 days. The specimens were subjected to compression loading, ensuring pin-supports with the use of fabricated ball and socket supports. A load cell was used to measure the compressive load applied to the specimens. Displacement transducers were also used during testing to measure the displacements occurring as the specimens were being loaded. During the test, a high-speed camera was utilized to record the type of failure the proposed ABRB would have.

However, due to the limitations imposed upon by the COVID-19 pandemic, the study was shortened accounting only the testing of the 1.5-m specimens and 2.0-m specimens. A total of 36 proposed ABRB specimens and 6 hollow specimens were tested for compression in this study.

3. RESULTS AND DISCUSSION

3.1 Mortar Characteristics

The mortar cylinders tested produced an average compressive strength for each mix design as seen in Table 1. The mix design with 0.7 W/C garnered the highest strength of 13.37 MPa while the mix design with 0.9 W/C produced the lowest strength of 9.075 MPa. This showed how adding water to the mix design could potentially decrease the average compressive strength. The weight and density of these mortar cylinders were also obtained to calculate the percentage void in the specimens. The very low percent difference shown in Table 1 indicates that the mix design had no significant effect on the density of the mortar samples.

Table 1. Mix Design Properties

Mix Design (W: C: S)	Ave. Comp. Strength (MPa)	Weight (kg)	Density (kg/m³)	Percent difference (%)
0.7:1:3	13.37	3.231	2057	1.13
0.8:1:3	12.86	3.195	2034	0.
0.9:1:3	9.075	3.211	2044	0.49

Legend: C=Cement, S=Sand, W=Water

Based on the study of Singh et al. (2015), the strength of mortar decreases as water content increases. The same trend was obtained in this research, although the values were lower as compared to those obtained by Singh et al as shown in Figure 2. The plot also suggests a strong linear correlation between the compressive strength and water to cement ratio (W/C) within the range of W/C used in this study.

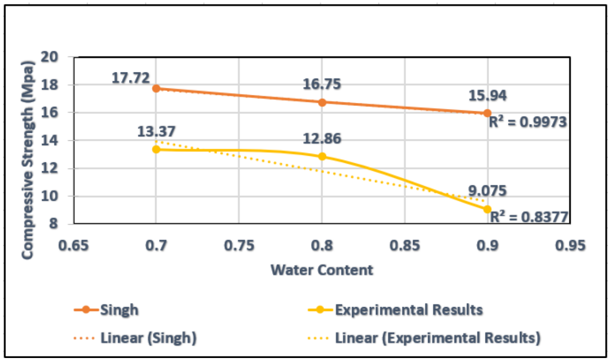


Fig. 2. Comparison of Mortar Compressive Strength

The void ratio of each specimen was calculated to determine its effect on the load capacity of proposed ABRB samples as well as its relationship with length. The void ratio is calculated using the formula below:

$$Void\ Ratio = \frac{V_m\rho-(m-ms)}{V_m\rho} \quad \text{(Eq. 1)}$$

where:

V_m = Volume of mortar in ABRB (m³)
ρ = Density of mortar (kg/m3)
m = Mass of ABRB (kg)
m_s = Mass of hollow steel tube (kg)

In Figure 3, the compressive load capacity is plotted against the void ratio. It is observed that there is a linear relationship between load capacity and void ratio. The larger the void ratio, the lesser is the compressive load capacity. Meaning, the proposed ABRB samples with less void spaces could sustain greater amounts of load.

Furthermore, the effect of length to the void ratio can be seen in Figure 4. It could be observed that in general, the void ratio increased as the length of the proposed ABRB increased. However, the rate of increase in void ratio varied with the W/C. Samples with 0.7 W/C showed drastic increase in void ratio while samples with 0.9 W/C showed less increase. The graph shown provided indications that as the length of proposed ABRB increases, higher W/C is needed to obtain the least void spaces.

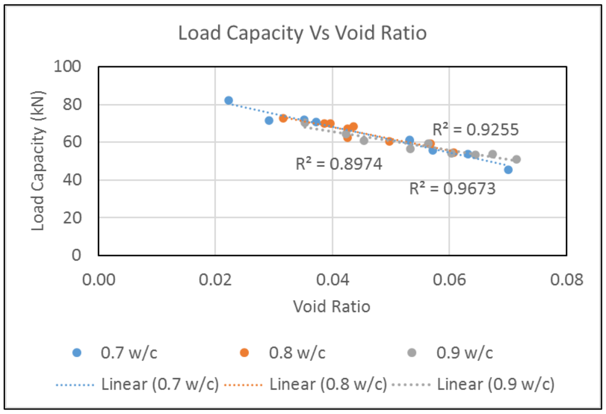


Fig. 3. Relationship of Load Capacity with Void Ratio of 1.5-m Proposed ABRB

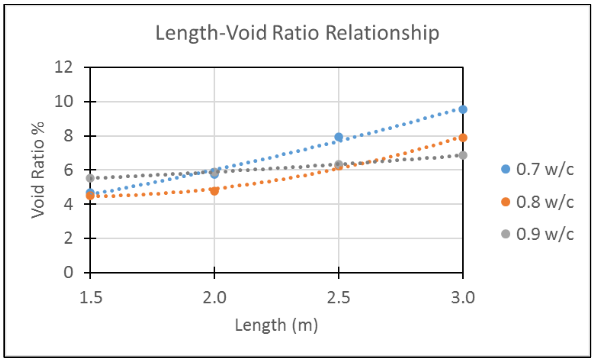


Fig. 4. Relationship of Length to Void Ratio of Proposed ABRB

3.2 Strength of Hollow Steel Pipe Specimen

In Table 2, the values of the experimental load capacities are compared to the theoretical yield strength and buckling strength. The theoretical strengths are calculated based on the formulas provided in the NSCP (2015). Table 2 shows that the experimental load capacities are closer to the theoretical buckling strength indicating that the failure mode is buckling. Moreover, the theoretical buckling strength is lower than the computed theoretical yield strength which further proved a buckling failure scenario. It can also be seen that the buckling strength (experimental and theoretical) decreases as the length increases.

Table 2. Comparison Between Theoretical and Experimental Load Capacities

Length (m)	Experimental Load Capacity (kN)	Theoretical Yield Strength (kN)	Theoretical Buckling Strength (kN)	$\frac{Exp.}{Theo.}$
1.5	31.025	59.043	33.690	0.92
2.0	25.354	59.043	21.666	1.17

3.3 Strength of Proposed ABRB Specimens

The theoretical strength of the proposed ABRB may be calculated assuming the specimens failed due to compression yielding. This is assuming that the steel reached the yield strength and the mortar reached 85% of its compressive strength which is the usual calculation procedure adopted for reinforced concrete columns. If the computed values are larger than the experimentally obtained strengths, then compressive yielding was not attained. Hence, it may be assumed that the specimens failed due to buckling. Shown in Table 3 are the theoretical compressive yield strength and experimental load capacities for the proposed ABRB specimens.

Table 3. Comparison Between Experimental and Theoretical Strength of 1.5-m Proposed ABRB

W/C Ratio	Exp. Load Capacity (0 Tamps) (kN)	Exp. Load Capacity (75 Tamps) (kN)	Exp. Load Capacity (150 Tamps) (kN)	Theoretical Yield Strength (kN)
0.7	54.126	62.217	74.817	85.666
0.8	61.049	62.884	70.807	84.640
0.9	52.876	56.295	65.135	77.114

The comparison of the theoretical compressive yield strength and the experimentally obtained load capacities shown in Table 3 indicated that the specimens failed due to buckling. Therefore, the proposed ABRB did not reach its full potential of becoming a full BRB. Although, it may still be considered as partially restrained because of the large increase in strength. Also shown is Table 3 is the effect of compaction of mortar on the strength of the specimens. It is clearly manifested that the strength increases with the increase in the number of tamps applied.

To further illustrate the increase in strength, a plot of the increased in strength of the proposed ABRB as compared to the hollow specimens is shown in Figure 5. It can be seen in Figure 5 that the proposed ABRB can increase the strength by as much as 141% or 2.41 times that of the hollow steel pipe. The lowest increase was recorded at 70% increase, which is considerably significant. The proposed ABRB sample with 0.7 W/C tamped 150 times produced the highest percentage increase when compared to the strength of hollow specimens.

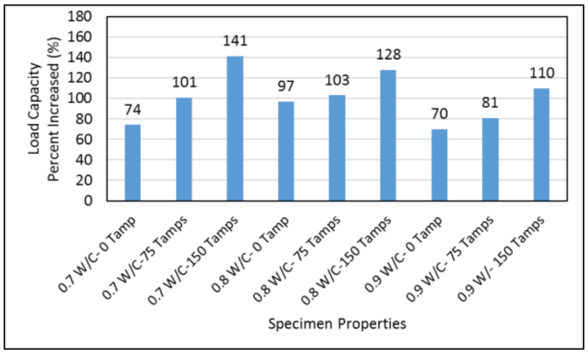


Fig. 5. Percentage Increased in Strength of Proposed ABRB Specimens

Analyses of the effect of the W/C and number of tamps on the strength of the proposed ABRB are shown in Figure 6 and Figure 7, respectively. Considering the effect of consistency (in terms of W/C) to the strength of the proposed ABRB, Figure 6 showed a trend on how increasing the W/C can lead to more flowy mixtures and decrease the strength of specimens. The effect of tamping could have been a significant factor on why the results found greater strength for W/C=0.8 than that for W/C = 0.7 in some cases. On the other hand, analyzing the effect of compaction (number of tamps) showed that the specimens which were applied with more tamps resulted to higher strength. Among those tested, the specimens tamped 150 times produced the highest load capacity as shown in Figure 7.

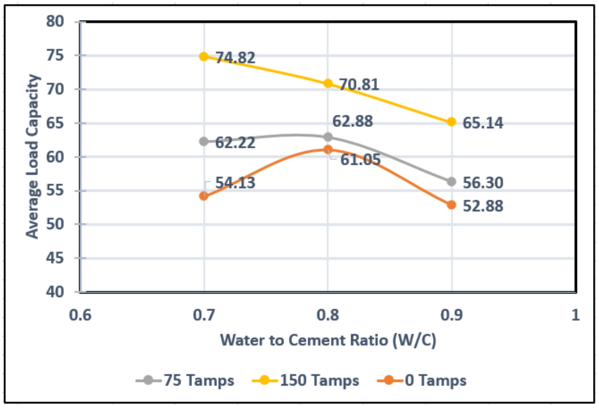


Fig. 6. Relationship of Load with Consistency for the 1.5 m Proposed ABRB Specimens

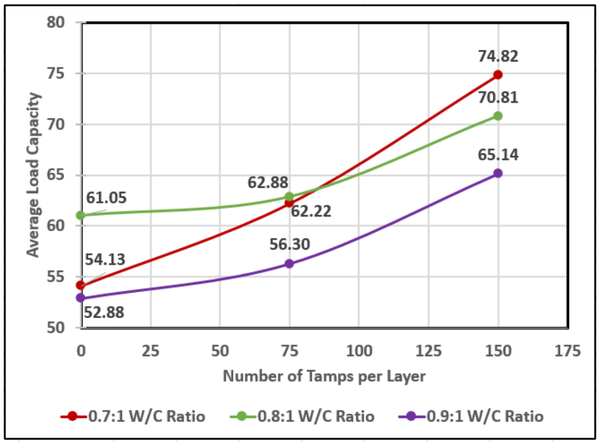
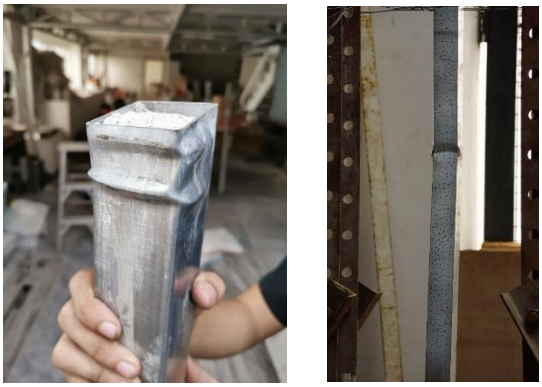


Fig. 7. Relationship of Load with Compaction for the 1.5 m Proposed ABRB Specimens.

3.4 Failure Demonstration of Specimens

Most of the proposed ABRB samples buckled at the middle-third of the span, some at the supports, while others experienced failure at both locations as seen in Figure 8. Buckling of specimens at supports could be explained by the fact that some mortar inside the hollow pipes settled after curing, thus affected the performance of the proposed ABRB, specifically the top portion. The locations at which the specimens buckled could have had significantly large void spaces which made those areas vulnerable to failure.



(a) (b)

Fig. 8. Failure Demonstration of Proposed ABRB (a) Buckling at Support (b) Buckling at Middle Part

4. CONCLUSIONS

The mortar specimen that produced the greatest load capacity while subjected under a compression load was the one with W/C of 0.7. Moreover, the effect of compaction was determined by tamping in each layer while the effect on consistency was based on the different W/C of the mortar infill. The proposed ABRB increased in strength in the range of 70% to 141% increase when compared to the hollow steel pipe specimens. The combination of 0.7 W/C and 150 tamps garnered the highest increase of strength while the combination of 0.9 W/C and 0 tamp produced the least. Therefore, the proposed ABRB specimen with the least W/C and greatest compaction in terms of number of tamps can produce the greatest overall strength. Specimens with 150 tamps were observed to have the greatest resistance to buckling since lesser void spaces were present. However, all the specimens tested under compression still failed in buckling, but in higher range. Thus, it can still be improved to attain higher buckling restraint. Furthermore, more efficient methods of pouring mortar to avoid high void ratio should be explored. It is recommended to consider larger cross-sectional area of the steel pipe and more efficient and stronger fillers to further increase the strength of proposed ABRB specimens. Lastly, further studies on the tensile capacity and the design connection can also be added as a continuation to the study.

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