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Development of Hybrid Braces Composed of Steel Tube, Cement Grout and Wood for Seismic Retrofitting

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Abstract

The authors have developed a new hybrid member composed of steel tube, cement grout and wood (WGFST). This is similar to a concrete filled steel tube (CFST). In the manufacturing process of the WGFST, the wood was set at the center of the section of the steel tube, and the cement grout was filled into the gap between the lumber and steel tube to rap the whole of the wood. The cement grout prevents the corrosion of inner woods.

The weight of the WGFST is lighter than that of CFST, and easier to manufacture, because the wood occupies the inner space of the steel tube mainly. The cement grout is available to get and cast than the high-flow concrete. The WGFST was developed to use to the seismic retrofitting brace for reinforced concrete structures. The advantages of the WGFST contribute to realize the easy setting of retrofitting members.

A test has been conducted to one-half scaling model of the short column specimens under concentric compression. The main test parameters were shapes of the steel tube and depth of the inner wood. The depth of the circular steel tubes and square steel tubes was 100mm. The axial stiffness and strength deceased according to the increase of the sectional area of the inner wood. After the basic investigation for the behavior of the short columns of WGFST, centrally loading test was conducted for the four long column specimens. These specimens buckled and attained the maximum strength. These results showed that the axial load carrying capacities were estimated by summation of bucking strength of each component.

The WGFST which were developed as the retrofitting members will be predicted to be slender braces in the actual situation. When the ratio of buckling length to depth of the member is over 10, the maximum strength is determined by the buckling strength which is dominated by the moment of inertia of areas both of steel tube and inner grout. In this case, the inner wood does not affect the axial load carrying capacities due to the wood locates at the center of the section. The weight and the axial load carrying capacity of long circular column with 50mm depth of wood were compared to the same size column without wood. The weight of the specimen with wood was 10% lighter than that of the specimen without wood. On the other hand, these capacities were almost the same. The results showed that the possibility of actual use of WGFST for the seismic retrofit.

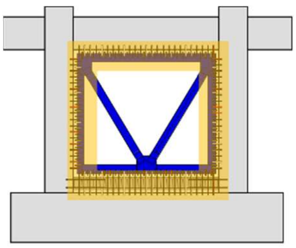
Keywords: *Composite columns; Seismic retrofit; Brace member; CFST; Axial loading test*

1. Introduction

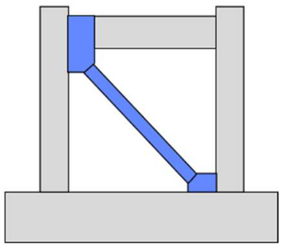
In Japan, retrofit method with steel brace frame for RC structure are always used as shown in Fig.1(a). Retrofitting with steel braced frame a lot of studs and anchor bolts are required to fix the steel frame and transmit the tensile stress of diagonal brace to the existing RC frame. However, this method needs heavy equipment and it is difficult to use particularly in rural area, constricted area or remote island.

For seismic retrofitting in the areas mentioned above, the authors have been developed a new seismic retrofitting method by using CFST (concrete-filled steel tubular) diagonal brace which act only compression [1, 2]. This method is named as CFST-SS retrofit [3, 4] and described in Chapter 2 detailedly. In this method, we set a steel tube to RC frame as shown in Fig.1(b) and pour high-flow concretes into the steel tube after. This method saves materials and constructing time to realize an economic seismic retrofit. However, there are requests from the real construction for this method. First, high-flow concrete is not available outside of Japan. Second, a simpler construction method is preferred. Therefore, the authors propose a new hybrid pre-cast member composed of steel tube, cement grout and wood (WGFST) as shown in Fig.2 to satisfie those requests.

As the characteristic of this new hybrid member is not comprehended yet, loading tests have been carried out with eighteen short columns and four long columns subjected to concentric axial force. Calculation methods of elastic stiffness and axial strength for WGFST are also introduced and compared to the test results.



(a) Retrofit with steel braced frame



(b) CFT-SS

Fig. 1 – Elevations of conservative and proposed way

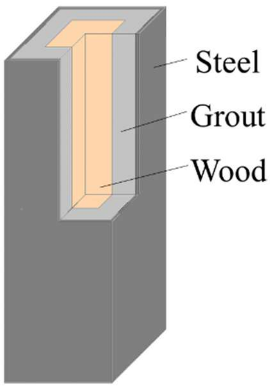


Fig. 2 – Image of WGFST

2. Details of retrofitted RC frames with CFST-SS

In this chapter, details of CFST-SS are described. Fig.3(a) shows the behavior of RC frame, that is retrofitted by CFST brace, under lateral force subjected from left side to right side. In this case, the brace touches the existing frame and bears the lateral force. Fig.3(b) shows the behavior under lateral force subjected from right side to left side. In this case, the brace departs from the existing frame and no axial force acts on the brace. In order to keep the right position of the diagonal brace in the case of Fig.3(b), a needle bearing was set at the top of the diagonal brace as shown Fig.4. As, Earthquake force acts in difference direction alternately. We have to set a pair of braces to resist lateral load from both sides as shown Fig.5.

The feature of our retrofit method includes easy calculation for lateral load carrying capacities of the retrofitted RC frames. As shown in Fig.6, we proposed the calculating methods with two failure modes of retrofitted frames. One is tensile yielding of the windward column as shown in Fig.6(a). The other is buckling of the diagonal brace as shown in Fig.6(b). In case of Fig.6(a), as the windward column is assumed to yield under axial tension force, this column does not bear bending moment and share force as well as lateral force. Thus, the bending moment diagram is drawn as Fig.7. The compression force N_b of brace and the lateral load carrying capacity Q_{mu} are calculated from equilibrium of the forces of the top of the windward column as shown in Eq. (1) and Eq. (2).

$$N_b = \frac{\sum_t W_t + N_y - Q_b}{\sin\theta} \tag{1}$$

$$Q_{mu} = \frac{\sum_t W_i + N_y - Q_b}{\tan\theta} + Q_c \tag{2}$$

Here, $\sum_t W_i$ is vertical force at the top of the column by the gravity load. N_y is tensile strength of the column which is calculated by sum of the tensile yielding strengths of longitudinal bars. Q_c and Q_b are the shear forces of column and the beam respectively. The feature of these equations is that the compressive force of brace can be expressed by the terms of other forces. Then, Eq. (3) is a condition to decide failure mode of retrofitted RC frame.

$$N_b \sin\theta > \sum_t W_i + N_y - Q_b \tag{3}$$

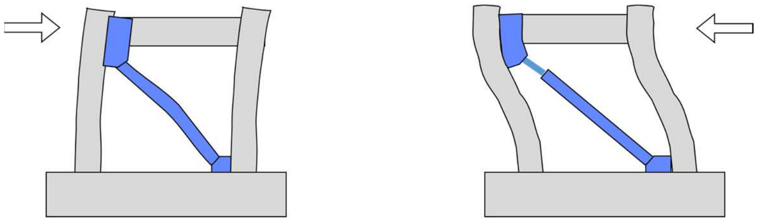
In the case of satisfying Eq. (3), failure mode is the tensile yielding of the windward column as shown in Fig.6(a). On the other hand, in the case of not satisfying Eq. (3), failure mode is buckling of the diagonal brace as shown in Fig.6(b).

In the case of Fig.6(b), the lateral force sustained by the windward column is negligible. The lateral load carrying capacity Q_{bu} is calculated simply as Eq. (4).

$$Q_{bu} = \alpha N_{cu}\cos\theta + (1-\alpha) Q_c \tag{4}$$

Here, N_{cu} is bucking strength of brace calculated by CFST recommendations [5] in Japan for example. The notations α_i is lateral force sharing ratio between brace and the windward column.

When the designer has chosen the failure mode of the tensile yielding of the windward column, it is necessary to use the diagonal brace which have small slenderness ratio. Because the length of the diagonal brace is fixed by the span length and story height, the diagonal brace will become the member with large sectional area. Sometimes, we cannot choose a brace with enough sectional area. In this case, we accept the failure mode of the buckling of the diagonal brace. The earthquake resisting behavior of the failure mode of the tensile yielding of the windward column is preferable than that of the bucking of the diagonal brace. However, there is an advantage for the latter failure mode as a slender member usually has lighter weight and possible to be set by only human power for the retrofit. It is valid to use in rural area, mountain side and isolated island, where it is difficult to use the heavy equipment for setting the braces. In the areas shown above, there are requests to decrease the weight of CFST brace. Also, there are requests to replace the high flow concrete, which is difficult to use in the areas, to more familiar material. In order to apply these requests, the authors developed new hybrid member composed of steel tube, cement grout and wood (WGFST). We are able to realize light weight brace by using the wood and replace the high flow concrete to cement grout. The structural property of WGFST is investigated experimentally in the following chapters.



(a) Compressive force (b) Tensile force

Fig. 3 – Behavior of the brace received lateral force

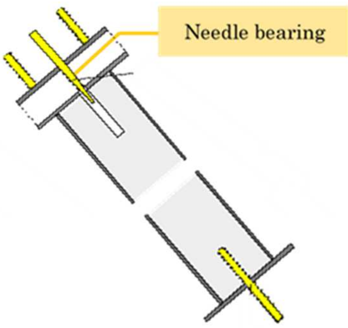


Fig.4 – Needle bearing of the top of the brace

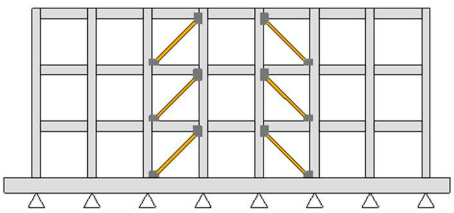
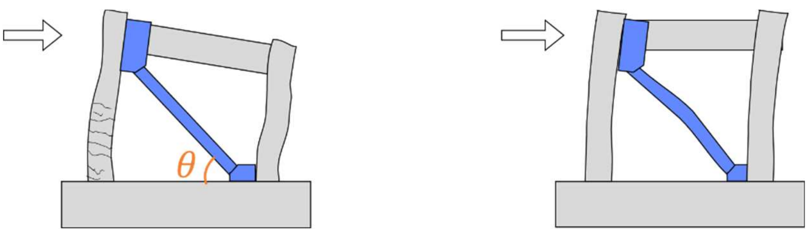


Fig.5 – Elevation of design method



(a) Tensile yielding of the windward column (b) Buckling of the diagonal brace

Fig.6 – Failure modes of retrofitted frames

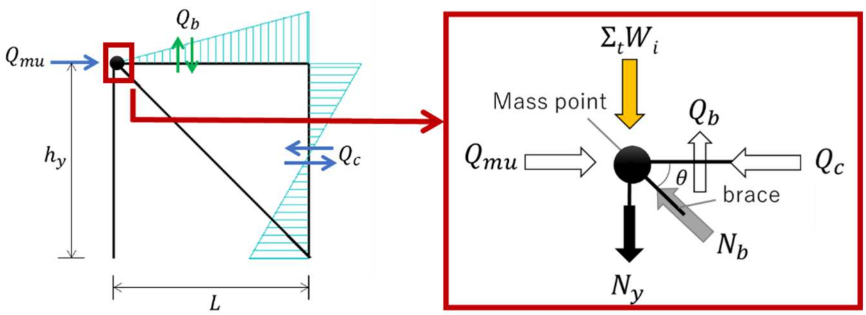


Fig.7 – Equilibrium of the forces of the top of the windward

3. Introduction of WGFST and loading test

This chapter describes the proposed hybrid member WGFST and loading tests with them. As described in Chapter 2, the buckling strength of brace is an important factor that affects the failure mode of the retrofitted RC frame with CFST-SS. In order to reduce weigh only and keep the buckling strength of brace, WGFST is proposed. As wood is set at the center, moment of inertia of area as well as buckling strength of WGFST are expected almost the same with CFST which has the same cross-section.

Therefore, in the manufacturing process of WGFST, the wood was set at the center of the section of the steel tube, and the cement grout was filled into the gap between the wood and steel tube to rap the whole of the wood. The cement grout prevents the corrosion of inner woods. Additionally, the weight of the specimen with wood is lighter than that of the specimen without wood and easier to manufacture because the wood occupies the inner space of the steel tube.

In this study, the authors have investigated the property of WGFST by two series of the test, which includes short columns and long columns. According to reference [5], the ratio of buckling length and outer depth (ℓ_k/D) is less than 4 for short column, and for long column ℓ_k/D is more than 12. From the tests with short columns, basic property of yield strength and stiffness of the WGFST is investigated. From the tests with long columns, the buckling yielding strength is investigated. Overviews of specimens and parameters are shown in Fig.8. Within the name of specimens, the first character means sectional shape. The second character means length of specimens. The third character means depth of wood. The fourth figure means number of specimens with same parameters.

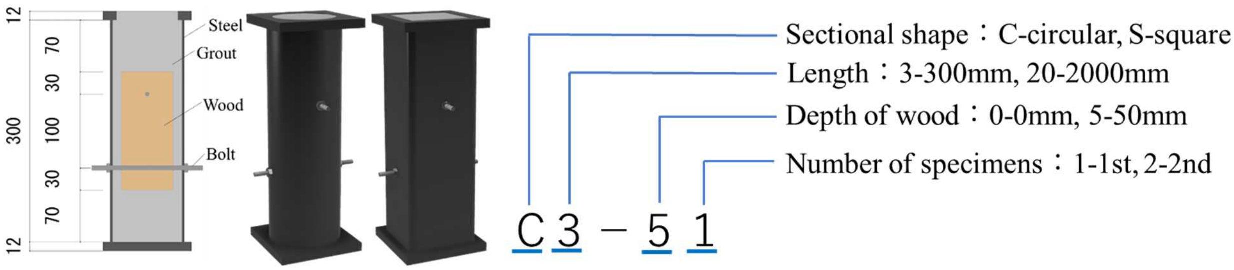


Fig.8 – Name and shape of Test column specimens

4. Axial compressive test with short columns

Test has been carried out on eighteen short columns subjected to concentric axial force. The axial compressive capacities between columns with or without inner wood was investigated by this test. Table 1 and Table 2 show the results of coupon tests of concrete and steel that is used in the short columns. Details of eighteen short column specimens are summarizes in Table 3. Boundary condition of top of the specimen is pin support and bottom of one is fixed support as shown in Fig.9.

Table 4 shows the test results and comparison between tests and calculation with the model proposed by the authors [6, 7]. The axial stiffness in Table 4 is determined by Eq. (5).

$$EA_{cal} = {}_sE \cdot {}_sA + {}_gE \cdot {}_gA + {}_wE \cdot {}_wA \tag{5}$$

Here, ${}_sE$, ${}_gE$ and ${}_wE$ are the elastic modulus of steel, cement grout and wood. ${}_sA$, ${}_gA$ and ${}_wA$ are the sectional area of steel, cement grout and wood.

The compressive yielding strength in Table 4 is determined by Eq. (6).

$$N_0 = {}_s\sigma_c \cdot {}_sA + {}_g\sigma_c \cdot {}_gA + {}_w\sigma_c \cdot {}_wA \tag{6}$$

Here, ${}_s\sigma_c$, ${}_g\sigma_c$ and ${}_w\sigma_c$ are the compressive strength of steel, cement grout and wood. Eq. (6) shows that the compressive yielding strength is estimated by summation of each of compressive strength.

The test results of elastic stiffness tend to be less than the calculation because the test values of EA_{exp}/EA_{cal} and N_{exp}/N_0 in Table 4 are almost under or near 1. Here, the subscript exp denotes results of loading test, and the subscript cal denotes calculation results. As a sample, results of C3-71 and S3-71 are shown in Fig.10. These test values (red line) are less than the calculated value (blue line). From Table 4 and Fig.10, the basic property of yield strength and stiffness of the WGFST are almost the same between loading test and calculation.

Table 1 – Material properties of concrete

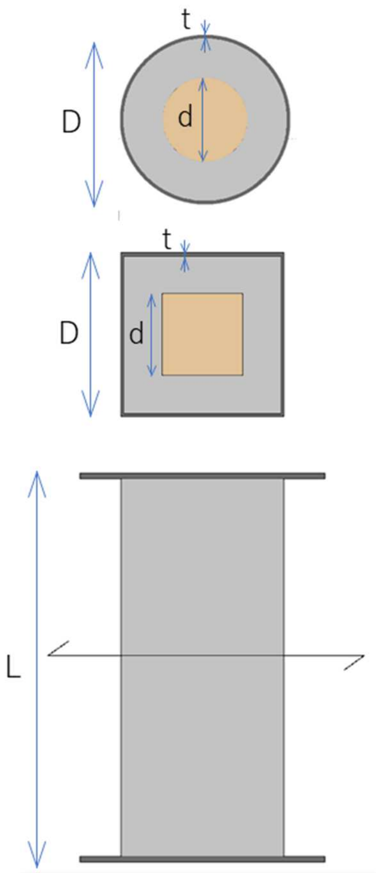
Compressive Strength	Young's Modulus
N/mm²	kN/mm²
67.9	32.1

Table 2 – Material properties of steel

Spec	Yield Stress	Young's Modulus
	N/mm²	kN/mm²
Round(STK400)	359	208
Square(STKR400)	357	195

Table 3 – Test specimens of short columns

Specimen	Depth	Thickness	Depth to Thickness ratio	Length	Diameter of wood
	D	t	D/t	L	d
	mm	mm		mm	mm
C3-00					
C3-01					0
C3-02					
C3-03					
C3-51	101.6	3.2	31.75	300	
C3-52					50
C3-53					
C3-71					
C3-72					70
C3-73					
S3-00					
S3-01					0
S3-02					
S3-03					
S3-51	100	3.2	31.25	300	
S3-52					50
S3-53					
S3-71					
S3-72					70
S3-73					



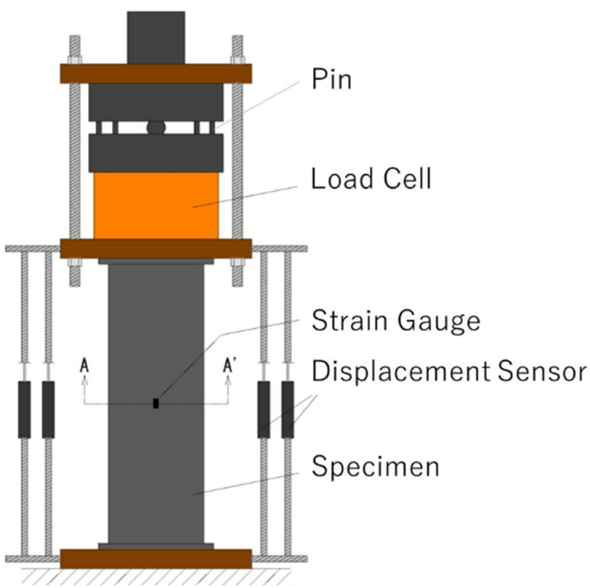


Fig.9 – Test method of short columns

Table 4 – Test results of short columns

Test Specimen	Axial Stiffness			Compressive Strength		
	EA_{exp} MN	EA_{cal} MN	EA_{exp}/EA_{cal}	N_{exp} kN	N_o kN	N_{exp}/N_o
C3-01	263		0.71	837		1.05
C3-02	326	370	0.88	825	799	1.03
C3-03	259		0.70	842		1.05
C3-51	276		0.82	731		1.03
C3-52	292	338	0.86	730	712	1.03
C3-53	284		0.84	636		0.89
C3-71	258		0.84	603		0.96
C3-72	270	308	0.88	587	628	0.94
C3-73	269		0.87	639		1.02
S3-01	429		0.99	1075		1.11
S3-02	529	434	1.22	1027	971	1.06
S3-03	411		0.95	1002		1.03
S3-51	422		1.07	811		0.94
S3-52	427	394	1.09	700	860	0.81
S3-53	399		1.01	807		0.94
S3-71	376		1.06	743		0.99
S3-72	374	355	1.05	681	754	0.90
S3-73	355		1.00	736		0.98

(a) C3-71 (b) S3-71

Fig.10 – Test results of short column specimens

5. Axial compressive test with long columns

This chapter describes test which has been carried out with four long columns subjected to concentric axial force. The buckling strength is investigated by this test. Table 5 and Table 6 show the results of coupon tests of concrete and steel that is used in the long columns. Details of four long column specimens are summarized in Table 7. Fig.11 shows test setup for long column. Both boundary conditions of top and bottom of the specimen are pin support. Specimens buckled and attained the maximum strength as shown in Photo 1. Table 8 shows the test results and comparison between tests and calculation with the model which is the same to chapter 4 [6, 7]. The axial stiffness in Table 8 were determined by Eq. (5) in chapter 4. The buckling strength in Table 8 is determined by Eq. (7) by summing the buckling yielding strength of each material [5, 9, 10].

$$N_{cr} = \frac{\pi^2}{l_k^2}({}_sE \cdot {}_sI + {}_gE \cdot {}_gI + {}_wE \cdot {}_wI) \tag{7}$$

Here, ${}_sI$, ${}_gI$ and ${}_wI$ are moment of inertia of area of wood, grout and steel.

As shown in Table 7, the specimens with wood are 10% lighter than the one without wood. Then, it is expected that the axial stiffness and buckling yielding strength deceased according to the increase of the sectional area of the inner wood. However, form Fig.12 which shows the test results of long columns, buckling yielding strength of GFST are also the same to them of WGFST. Note that, we called the specimen without wood as GFST.

Table 5 – Material properties of concrete

Compressive Strength	Young's Modulus
N/mm²	kN/mm²
70.6	29.9

Table 6 – Material properties of steel

Spec	Yield Stress	Young's Modulus
	N/mm²	kN/mm²
Round(STK400)	383	202
Square(STKR400)	416	208

Table 7 – Test specimens of long columns

specimen	Depth	Thickness	Depth to Thickness ratio	Length	Diameter of wood	Weight
	D	t	D/t	L	d	
	mm	mm	—	mm	mm	kg
C20-01	101.6	3.2	31.8	2000	0	55
C20-51					50	49
S20-01	100		31.3		0	66
S20-51					50	59

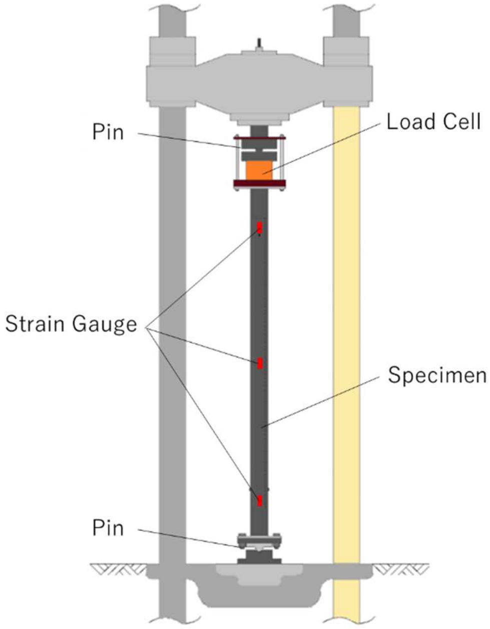


Fig.11 – Test setup

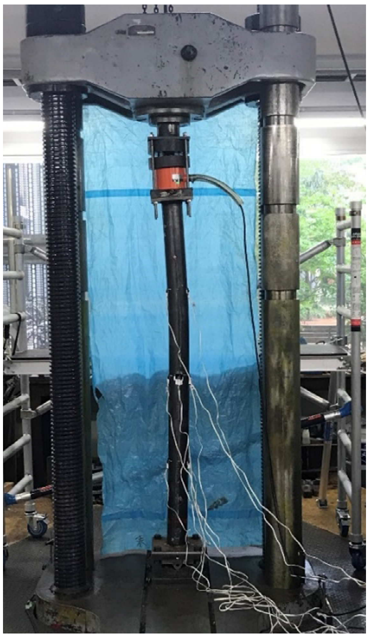
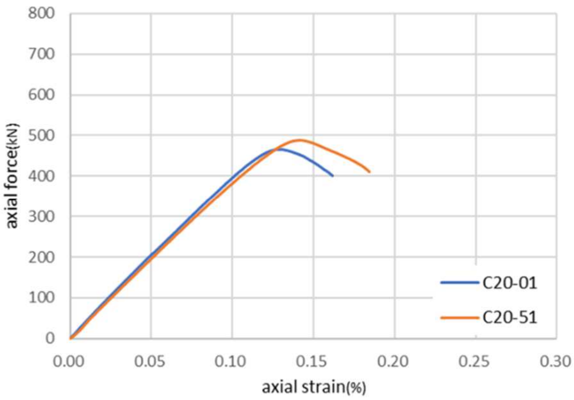


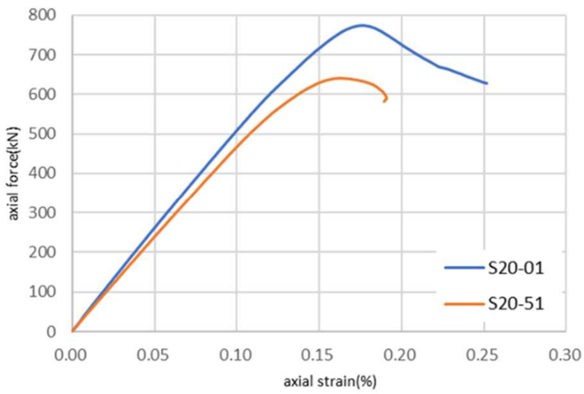
Photo.1 – Failure situation

Table 8 – Test results of long columns

Specimen	Axial Stiffness			Compressive Strength		
	EA_{exp}	EA_{cal}	EA_{exp}/EA_{cal}	N_{exp}	N_{cr}	N_{exp}/N_{cr}
	MN	MN		kN	kN	
C20-01	410	413	0.99	466	494	0.94
C20-51	392	368	1.07	489	463	1.06
S20-01	518	509	1.02	775	716	1.08
S20-51	476	452	1.05	640	659	0.97



(a) Circular section

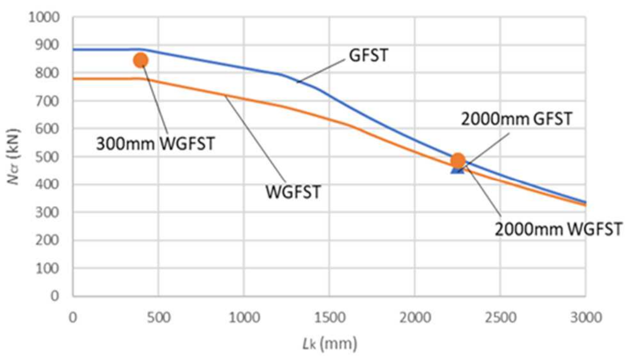


(b) Square section

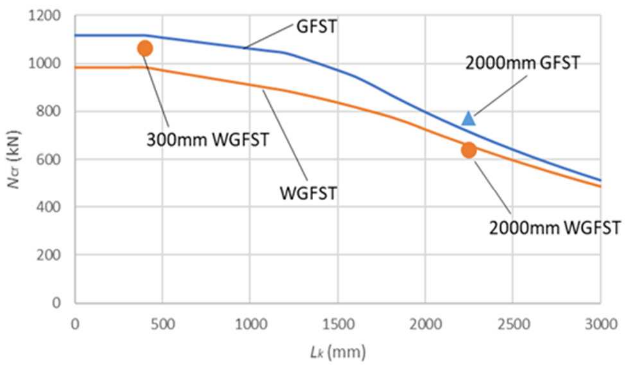
Fig.12 – Force-strain relations of long column specimens

Fig.13 shows the relation between buckling strength N_{cr} and buckling length l_k. The plots show the test results and the lines show the calculated buckling strength. The test results of the 300mm short column specimens are plotted between the calculated strength of WGFST and GFST. The results of the 2000mm long column specimens are also plotted near the two calculated strength. Thus, the buckling yielding strength of WGFST can be calculate easily by Eq. (7).

The WGFST which were developed as the retrofitting members will be slender braces in the actual situation. When the ratio of buckling length to depth of the member is over 10, the maximum strength of brace is determined by buckling, and the influence of inner wood is very small. Additionally, there is not a difference in the compression strength between WGFST and GFST as shown in Fig.13, but the decreasing of weight appears as shown in Fig.8. These results showed that actual using the WGFST as seismic retrofit is possible because WGFST improves the effect of construction and gets yielding strength which is almost the same to GFST.



(a) Circular section



(b) Square section

Fig.13 – Relation between N_{cr} and l_k

6. Conclusions

The following conclusions can be reached by this study:

1. The axial stiffness and maximum strength are almost the same to calculation.
2. WGFST was 10% lighter than the column without wood.
3. The materials are saved and available than CFST.
4. The construction time is saved than CFST.
5. The possibility of actual use of WGFST to the seismic retrofit because these capacity of WGFST is almost the same to the column without wood.

7. Acknowledgements

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