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Case study of an aged paper tube structure

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ABSTRACT

The paper tube structure was installed on a rectangular area of 10 m x 15 m and covered with polycarbonate panels built on September 17, 1995 to serve as a temporary building for the Takatori Catholic Church in Japan. The interior of the church adopts an oval design, which is based on the church designed by Bernini in the 17th century in Italy. It is made of 58 paper tubes with a diameter of 330 mm. The wall is 15mm thick and 5m high. A case study was conducted to evaluate the mechanical properties of aged paper tube structure used over 10 years in Japan. These experimental tests include compressive strength, axial tensile test, tensile elongation test, flat crush compressive test, hardness test, and bending strength test for the elastic modulus. These test results indicate that the difference of hardness values and elastic modulus for new and old tube structure in Shigeru Ban projects is less than 5%; it is telling that old paper tube is still available for loading. The fact is that the aged paper tube structure has endured over 25 years of service in Japan and Taiwan environments. The expected lifetime of the paper tube structure affected by the environmental impact estimated at ten to twenty years. Therefore, the paper Dome maybe still be required for conducting a preliminary inspection and maintains public safety in the further.

Keywords: Paper tube, Compressive strength, Paper dome, Tensile elongation, Hardness.

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1. INTRODUCTION

Due to rising environmental concerns designers and engineers have already started incorporating elements that enhance contribution of their product towards innovative, eco-friendly and sustainable building studied by Manzini (2009). In case of building and construction industry, innovative and green building material is frequently designed and experimented but is usually not as strong as conventional building materials like steel and concrete. An intelligent design is certainly required which can optimize the materials and make it more efficient and thus make it competitive to conventional materials in terms of strength and stability parameters of the building. With the help of proper optimization techniques, structures made out of weak but sustainable materials like paper tubes in Paper Dome as stated by Bank and Gerhardt (2016), which have a very low embodied energy as compared to concrete, steel, clay-brick and glass could be made as strong, long lasting, structurally stable as conventional structures as described in early works (Monticelli et al., 2013; Cripps, 2004; Hammond and Jones, 2008). The cost comparison of simple temporary housing or shelter is showed in Table 1 as stated by Cripps (2004). Paper tube house is the lowest cost of temporary housing.

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Table 1. Cost Comparison of Simple Temporary Housing

Type / Item	Modular house	Cabin	Container house	Tin house	Bamboo House	Tent house
Cost (USD/m^2)	101	202	116	101	123	26
Type / Item	Paper tube house	Aluminium house	Plastic steel house	Trailer house	Precast house	Caravan house
Cost (USD/m^2)	13	250	252	250	267	100

Structures made out of paper tubes are extremely lightweight and fragile, hence the analytical modes of estimation in engineering them, the accounted safety factor and the precision in production and execution is significantly larger than conventional structures, whose failure modes, experimental and statistical data and heritage knowledge is fairly easily accessible, in order to ensure safety of the users, and to adhere to codes of practice, where such norms may not exist. It is the duty of the architectural engineer to achieve a designed architectural form, while keeping in consideration the limitations of the building materials as well as elegance of the designed form. This type of design results into an articulated as well as aesthetically pleasant form. Paper tubes which are used in packaging and transport industry are hollow cylindrical members which are made by repetitive spiral overlapping of recycled paper in over a mandrill using adhesives as stated by Dunlap (1961) and Kirwan (2013). The strength of the paper tube may not be as much as other conventional building materials but with intelligent optimization techniques, use of geometry to streamline types of forces and combinations with other materials, paper tubes can become a formidable option for a thoughtful, ecologically sensitive and an efficient building material as studied by Correa (2004).

The service life of a building and its components will affect the maintenance and environmental impact of the building. The life expectancy of the cardboard house designed by Ayan (2009) has estimated to be 15 years. The cardboard structure of the Westborough School designed by Cottrell and Vermeulen Architecture, and built by BuroHappold is estimated to be 20 years old. This after-school club constructed with paper tubes and cardboard wall panels was built in 2001. It has a history of 16 years and is still in use today. Many building materials and their elements have short maintenance intervals. There are two possible ways to deal with the impact of buildings on the environment: extending the life of the building and choosing materials with lower energy consumption. In terms of paper tube and cardboard structure, the latter option will provide better results. It is difficult to estimate the maximum service life of a building composed of paper tubes and cardboard, as there are only a few examples currently constructed as permanent structures. However, from these examples, it can be assumed that the service life of paper tube buildings is approximately 15 to 20 years as stated by Ayan (2009).

A cardboard building with a life expectancy of 25 years was developed as an on-site innovation project to explore and solve practical problems surrounding design, manufacturing and construction, cost, and the use of alternative building materials as studied by Cripps (2004). Table 2 shows the performance comparison of paper and traditional building materials as stated by Latka (2017). Similar to paper, wood is an anisotropic material. The elastic modulus, ultimate stress (tension and compression), and weight density properties of paper are comparable to wood and polyethylene materials.

Table 2. Comparison of the properties of paper and traditional building materials

ISOTROPIC	Modulus of elastic, GPa		Ultimate stress, MPa: Compression		Ultimate stress, MPa: Tension		Density kN/m^3	Fracture energy, MJ/kg	Recycling
Concrete	29		20		2.2		24	1.9	downcycle
Ceramics	60~470		200~3000		200~1000		30~60	4~8	recycling
Steel	210		360		360		78.5	25	recycling
Glass	70~75		700~900		30~90		24	13.7	recycling
Polyethylene	0.6~0.9		20~30		20~45		9.5	80.9	recycling
ANISOTROPIC	‖	├	‖	├	‖	├			
Softwood	8.5~11	0.6~0.9	35~45	3~9	30~80	3~4	4.5~6	4.7	recycling
Paper	2~20	0.5~10	5~10	2~5	15~45	5~20	6~9	5~20	recycling
Solid board	3.5	1.6	8.0	5.6	27.1	13.5	6~9	9.4	recycling

‖ wood in grain direction, paper – machine direction
├ wood in perpendicular to grain direction, paper – cross-machine direction

A study used experiments to find out the structural behaviour and characteristics of paper tubes. This study discussed the possibility of using paper tubes to construct buildings. These experiments include compressive strength test and bending strength test to obtain the elastic modulus, critical buckling stress, yield stress and ultimate stress of the paper tube. In addition, this study also conducted experiments on the plane frame to resist the load of the material testing system (MTS). The purpose of these experiments is to obtain the mechanical properties, failure types and bearing capacity of the paper tube structure as studied by Huang (2003). It found that large-diameter paper tubes are weaker than small-diameter paper tubes because their paper is wound at a larger angle with respect to the tube axis, and also made recommendations for the mechanical properties of the paper tubes. Maximum compressive, tensile and flexural strength: 0.8 MPa, creep coefficient is 0.1. The load at the attachment should not exceed 1.4 MPa. Maximum strength of peeling glue: 0.3 MPa. Young's modulus is 1-1.5 Gpa, and it is monitored throughout the life of the material as stated by Latka (2017).

2. MATERIALS AND METHODS

Paper tubes, also known as hollow paper cores, have been used throughout the world in the construction industry as formwork for circular columns and are the most popular products of the paper industry used by famous Japanese architect Shigeru Ban's architectural projects. Paper Dome is a church made of giant hollow paper tube structure supported by an oval of 58 tubes, 5.0 meters in height. The outer diameter of tube is about 33 cm and the wall thickness of paper is about 1.5 cm. The roof of the church is made of tent material. Ten years later, the paper church was demolished in June 2005, and all materials were sent to the Taiwan New Land Foundation as stated by Latka (2017). The New Hometown Foundation commissioned the paper tube building materials to conduct tests at Chaoyang University of Technology. This research investigates the mechanical properties of old paper tube of paper Dome used over 10 years in Japan. As the properties of paper tubes can vary depending on the material used, aged, relatively humidity, diameter or on the winding angle, which will affect the mechanical properties of the tubes. Therefore, it is common to test tubes before they are incorporated into a structure as studied by Latka (2017). These experimental tests include axial compressive strength, axial tensile test, tensile elongation test, flat crush compressive test, elastic modulus, hardness, and freeze-thaw cycle test from the aged paper tube study. Among them, the freeze-thaw cycle test is explained as follows.

The freeze-thaw cycle test is a part of durability testing and it was chosen as an accelerated degradation environment to evaluate the aging state of the paper tube material in this study. The freeze-thaw cycles of all samples were performed using the cold climate test equipment of Chaoyang University of Science and Technology in Taiwan. The paper tube material is subjected to a freeze-thaw cycle at a rate of 1 cycle/185 minutes, frozen in cold air at -18°C for 1.5 hours, and then thawed in wet air at 4.4°C for 1.5 hours. This testing method is close to ASTM C666 procedure B (2003), which is fast freezing in the air and thawing in water. The paper tube specimens were subjected to 0, 100, 200, 300, and 600 freeze-thaw cycles. Before and after the freeze-thaw cycle, the samples were tested for weight loss, hardness, and infrared inspection.

3. RESULTS AND DISCUSSION

3.1 Results of Axial Compression and Flat Crush Compression Test

The paper tube (with outer diameter and inner diameter were 33 cm and 30 cm respectively) were prepared and tested according to ASTM D4577 (2019) standard test method by investigating the axial compression resistance of a paper column under constant load. Axial compression was tested on old paper tube (whose outer diameter and inner diameter were 33 cm and 30 cm respectively) at a speed of 1000 kg/min and a maximum compression deflection of 100 mm. The specimen used in the compression tests was 500 cm long, as displayed in Fig. 1 (a). The result shows that old paper tube can bear up to 6936 kgf (68,019 N). The axial compression strength is equal to 6.04 MPa. When subjected to axial compression test, a tube may be pressed, buckled or wrinkled depending on the diameter and length of the tube, as shown in Fig. 1 (b). The compression strength was observed with a reduction as high as 30% at the aged condition compared to the initial one in Shigeru Ban project.

Flat crush testing is a measure of the load bearing capability of paper tube to loads acting perpendicular to the horizontal side and it was tested on old paper tube at a displacement of 25.4 mm per minute for testing bench seat support. The flat crush test is showed in Fig. 2 (a). Three specimens used in the flat crush tests were 50 cm long and it showed with the following results: 14.7 N/cm2, 14.7 N/cm2 and 15.2 N/cm2 (see Table 3). Although each paper tube bench weighs no more than 60 kg, it is able to support weight up to 1500 kg each, equivalent to the weight of 20 people, as shown in Fig. 2 (b).

Fig. 1. (a) Paper tube axial compression testing (left), (b) Wrinkles caused by axial compression (right)

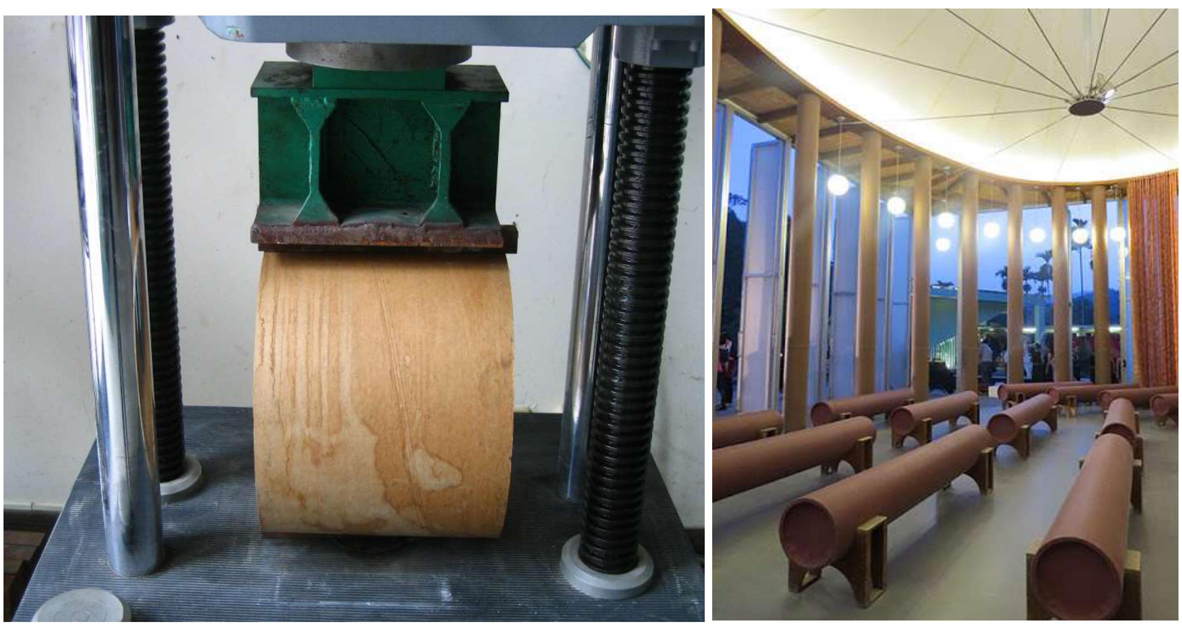

Fig. 2. (a) Flat crush test conducted by universal testing machine (left), (b) Paper tube bench (right)

Table 3. Mechanical properties of old paper tube used in Paper Dome

Sample	Tensile elongation test			Flat crush strength	Flexural strength	Hardness
	Strength	Elongation	Elastic modulus			
#1	17.6 MPa	6.15 %	2.86 GPa	14.7 N/cm^2	8.4 MPa	57.0
#2	15.9 MPa	7.14 %	2.23 GPa	14.7 N/cm^2	8.1 MPa	56.0
#3	14.5 MPa	7.72 %	1.88 GPa	15.2 N/cm^2	7.8 MPa	54.0
Avg.	15.9 MPa	7.07 %	2.25 GPa	14.9 N/cm^2	8.1 MPa	55.7

3.2. Results of Axial Tensile elongation, Elastic Modulus and Hardness Test

ASTM D828 (2016) is a test standard used to determine the tensile properties of paper tubes and paperboards using constant elongation equipment. Tensile elongation was tested for determining tensile properties of old paper tube at a displacement of 25 mm per minute. The dimension for test specimens required for performing this test method is 25 mm (1in) wide and 100 mm (4in) long with a dog bone tensile test sample for clamping in the instrument grips, as shown in Fig. 3 (a). The dog bone specimen has a gauge at each side and is designed to ensure the highest probability that the sample will fail in the maximum tensile loading, as displayed in Fig. 3 (b). Reject any value where the specimen slides in the grips, breaks in the clamping area, or shows signs of uneven stretching across its width, and rejects any value where the specimen breaks within 5 mm of the clamping area. Five specimens used in the tensile tests and two of the specimens are rejected, and it showed with the following results: 17.6 MPa, 15.9 MPa and 14.5 MPa (see Table 3). The tensile elongation of the tubes that was measured in the tests was 6.5% to 7.72% in a relative humidity of 80%.

The elastic modulus of paper tube is of great interest for design of paper tube structures and condition assessment of existing Paper Dome. Elastic modulus is calculated on the basis of the data obtained from tensile strength elongation test are displayed in Table 3. The tensile strength of paper tubes is approximately twice as high as their flexure strength, as shown in Table 3. The flexure strength of paper tubes is approximately 40% higher than their compressive strength. Elastic modulus (2.25 GPa) as obtained in the flexure strength test is very close to the Paper House and Paper Dome test results obtained by Shigeru Ban, which ranged from 2.17 to 2.36 GPa, as stated by Latka (2017) in Table 4. The difference of Elastic modulus for Paper Dome in Shigeru Ban projects is less than 5% at the aged condition compared to the initial one. In considering the differences between these test results, the source of the material, test method and moisture content should be considered. It described the basic principles of paper tube structure design, and made recommendations on the mechanical properties of the paper tube as maximum compressive, tensile and flexural strength: 0.8 MPa, and a creep coefficient of 0.1. Young's modulus is 1-1.5 Gpa and is monitored throughout the life cycle of the material. The above-mentioned test results of maximum compression, tensile, flexural strength and Young's modulus are all greater than the recommended value of paper tube structure design as studied by Latka (2017).

The Shore hardness test is a quick and convenient way to measure hardness of plastics and composites. The Shore D hardness technology uses the ASTM D2240 (2015) test method to measure the indentation depth of the indenter. Average hardness value for old paper tubes using Shore D hardness test is approximately 56, as shown in Fig. 4. The hardness value for new paper tube is 58. The difference of hardness values for new and old paper tubes is less than 4%. That means old paper tube is still available for loading.

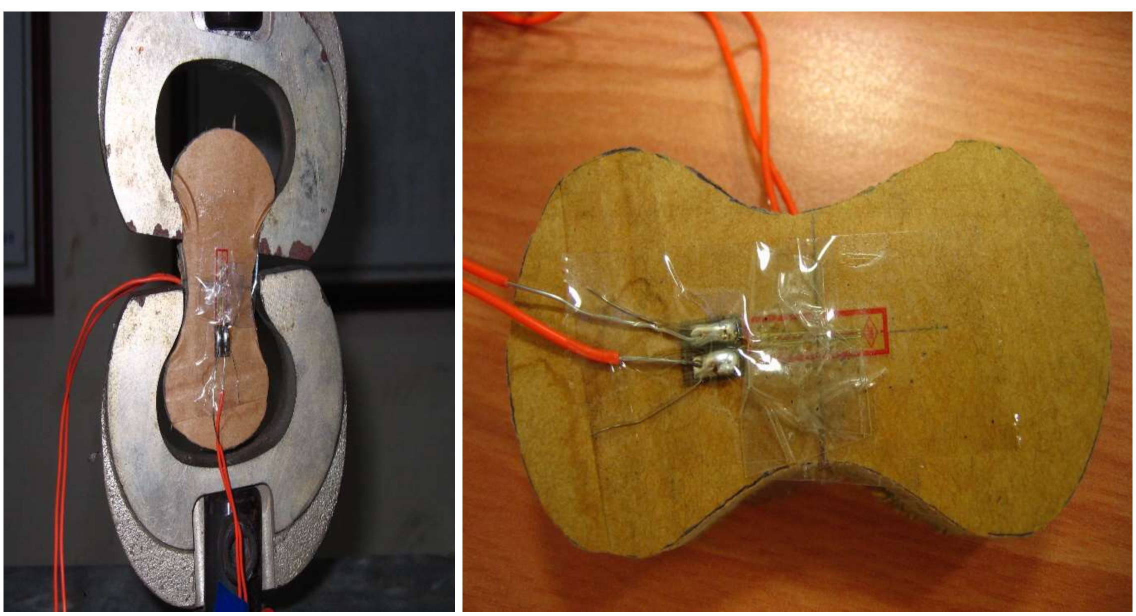

Fig. 3. (a) Dog bone tensile test (left), (b) *Dog bone tensile test* specimen (right)

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Table 4. Properties of paper tubes used in Shigeru Ban projects

Item / Project	Tube ID, t (mm, mm)	Moisture content	Compressive strength	Young's modulus	Flexural strength
Library of Poet	100,12.5	-	10.12 MPa	1.83 GPa	-
Paper House	280,15	8.8 %	11.17 MPa	2.36 GPa	16.8 MPa
Paper Dome	291,20	10.0 %	9.74 MPa	2.17 GPa	14.9 MPa
Japan Pavilion	120,22	8.7 %	9.53 MPa	1.57 GPa	14.5 MPa
Old Paper Tube	330,15	12.0 %	6.04 MPa	2.25 GPa	8.1 MPa

Fig. 4. Paper tube using Shore D hardness test

3.3 Results of Freeze-Thaw Cycle Test

The freeze-thaw resistance of the material was tested according to ASTM C666 procedure. The specification requires the sample to be repeatedly cycled between +4.4°C and -18°C for 185 minutes each cycle. In general, the premise of this test is that repeated freezing in air and thawing in air will cause microscopic degradation of the material, resulting in cracks, weight loss and reduced its strength. Fig. 5 provides the results of appearance photo and captured thermal image of paper tubes after 600 cycles of freeze-thaw testing. In general, the paper tubes were prone to damage caused by liquid or water. Two paper tubes don't occur distorted swelling or crack in Fig. 5 (a) and 5 (b) photos after 600 cycles of freeze-thaw testing. The main reason should be that the paper tube test sample was not immersed in water for freeze-thaw cycle test. However, water marks appear on the surface of two paper tubes. By using a captured thermal image for infrared inspections after 600 cycles of freeze-thaw testing, it looks like a flawless appearance in Fig. 5 (c) and 5 (d) photos.

Table 5 provides the results of the hardness value and weight of two old paper tube samples after 100, 200, 300 and 600 freeze-thaw cycles. The average hardness value for old paper tubes at 0, 100, 200, 300 and 600 cycles were 52.8, 52.3, 52.7, 52.8 and 52.3, respectively, compared with the corresponding value of 58 for the new paper tube. The difference of hardness values for new and old paper tubes after the freeze-thaw testing is less than 10%. A minor difference in weight was found after freeze-thaw testing.

Fig. 6 provides the results of percentage of hardness ratio and weight loss of paper tubes after 600 cycles of freeze-thaw testing. Both hardness ratio and weight loss had same trend, two steady and constant curves were found after freeze-thaw testing for old paper tubes. The variation of percentage of hardness ratio and weight loss of paper tubes before and after freeze-thaw test is very small and less than 5%. The old paper tubes for this laboratory study had a good freeze/thaw performance on hardness and weight loss results due to thawing in wet air at 4.4°C and not in water.

3.4 Paper Dome Regeneration in Taiwan

The Paper Church was delivered to Taiwan in 2006 and is located in the "New Hometown Park" in Puli, central Taiwan. The main structure of the building is composed of 58 paper tubes and the elliptical spaces are arranged. The intervals are arranged so that the inner and outer squares are integrated, allowing the space to expand. The PC steel frame is used to surround the paper tube to create a buffer zone inside and outside. The church columns and benches are made of paper tubes and the sun shines directly on the roof, creating a sacred atmosphere for the church. Construction work and procedure of the paper tube church are studied by Latka (2017) and Lee (2007) as following: (1). Lofting and excavating to bury the cylindrical base, (2). Paper tube base and pavement, (3). Paper tube lifting and installation, (4). Paper tube top ridge plate connection, (5). Roof stainless steel outer frame and push window, (6). Roof waterproof canvas and paving connecting board. The Paper church is currently open for visit and performance as shown in Fig. 7.

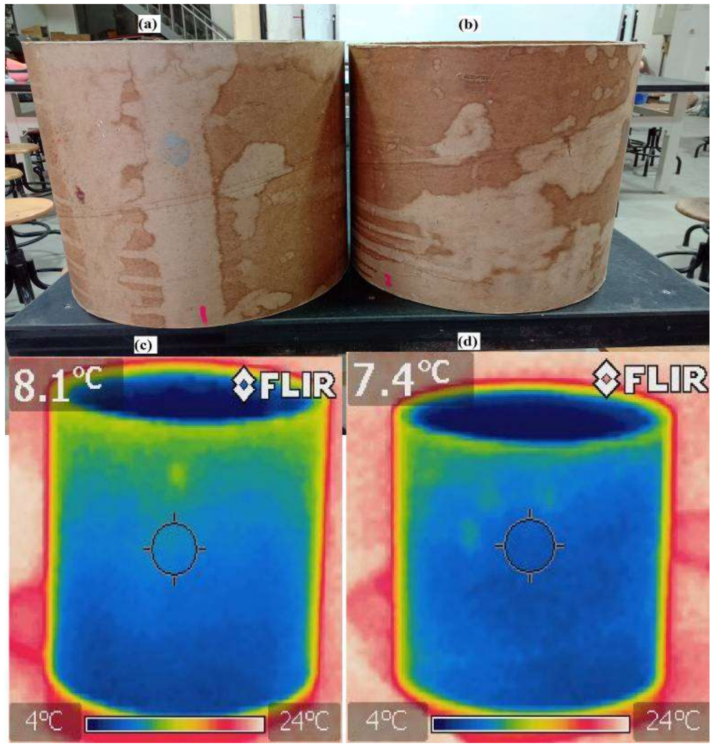

Fig. 5. Appearance photo and captured thermal image of paper tubes after 600 freeze-thaw cycles

Table 5. Hardness value and weight of two paper tube specimens after freeze-thaw cycling test

Freeze-Thaw Cycle		#0	#100	#200	#300	#600
Hardness value	#1	51.67	51.33	51.67	52.33	51.67
	#2	54.00	53.33	53.67	53.33	53.00
	Average	52.83	52.33	52.67	52.83	52.33
Weight (kg)	#1	3.10	3.10	3.20	3.20	3.10
	#2	3.06	3.06	3.15	3.14	3.09
	Average	3.08	3.08	3.18	3.17	3.10

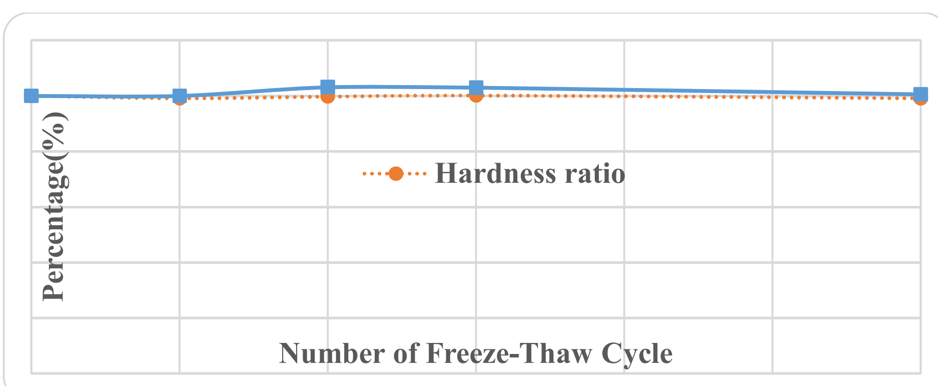

Fig. 6. Percentage of hardness ratio and weight ratio of paper tubes after 600 freeze-thaw cycles

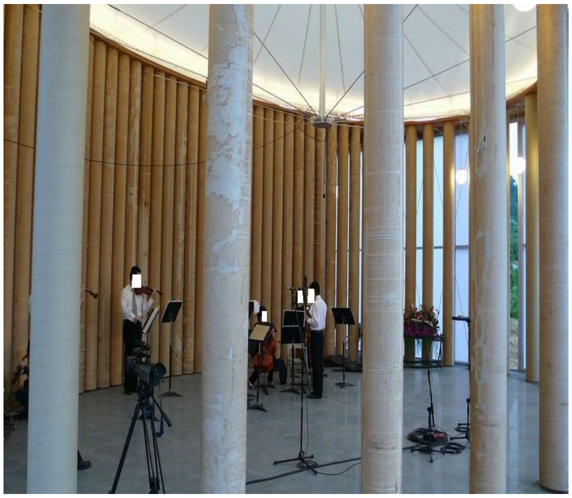

Fig. 7. Paper church open for visit and performance

4. SUMMARY

The Paper Dome is held up by 58 paper columns and even the bench chairs in the church were made using paper tubes and coated with an external water-resistant paper protective covering made in Puli Township. The following are the inferences made from the aged paper tube study.

1. The great risk for a paper tube structure is the moisture content of its paper material being affected by direct contact with water, rain or high humidity in Taiwan.
2. As for the paper column, it is able to support pressure up to 6936 kg each. The compression strength was observed with a reduction as high as 30% at the aged condition compared to the initial one. However, the difference of hardness values and elastic modulus for new and old Paper Dome in Shigeru Ban projects is less than 5%. That means old paper tube is still available for loading. And a wooden base connection for paper column plays a vital role by transferring designed loads.
3. Although each paper tube bench weighs no more than 60 kg, it is able to support weight up to 1500 kg each by the flat crush compression test, equivalent to the weight of 20 people. In order to meet various needs and performances of paper-tubes, the further study for vertical and horizontal compression of paper-tubes is needed.
4. The old paper tubes for this laboratory study had a good freeze/thaw performance on hardness and weight loss results due to thawing in wet air at 4.4°C and not in water. By using a captured thermal image for infrared inspections after 600 cycles of freeze-thaw testing, it looks like a flawless appearance.
5. Early use of paper tube in architecture concerned mainly temporary and emergency relief houses. However, the Paper Dome lasted surprisingly long and has endured over 25 years of service in Japan and Taiwan environment, the further inspection is required.

FURTHER RESEARCH

This case study on an aged paper tube structure used over 10 years as a primary research. Further research on paper in architecture should focus on how to improve the properties of paper and conducting an inspection and maintains public safety for aged paper Dome.

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