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Portals to an Architecture: Design of a temporary structure with paper tube arches

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ABSTRACT

Sustainable recyclable paper and composite materials can be ideal choices for the construction of temporary structures for both exhibition spaces or for rapid-recovery shelters in emergency operations. The unique engineering and sustainable features of these structures need to be considered as an integral part of the design process from the conceptual phase. Engineering studies to analyze these structures should be as important as the overall artistic and architectural vision. This paper examines the use of environmentally creep-formed paper tubes for the design, construction, and exhibition of, "*Portals to an Architecture*", a large temporary outdoor sculpture.

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1. Introduction

Recyclable paper and composite materials are excellent choices for the construction of temporary structures for both exhibition spaces or for rapid-recovery shelters in emergency operations. Specifically, large diameter (100 mm and greater) paper tubes (aka "cores") used in the printing and converting industries [17] can be used in innovative ways that take advantage of their material properties, recyclability, and low cost. Spirally wound paper tubes are highly engineered structural products made of different grades of paper board [8] and are used principally in the paper and fabric industries for supplying sheet and fiber materials. In building construction they are used as disposable forms for concrete columns known as "Sonotubes" [16]. Architecturally, paper tubes have been used in column, beam, and shell type configurations for both permanent and temporary structures. Less frequently, paper tubes have been utilized in curved applications, which often requires additional structural supports.

Architect Shigeru Ban is well known for his use of paper tubes in a variety of applications [13]. Following the Hanshin-Awaji earthquake in 1995, Ban utilized paper tubes for the main structural wall elements to construct temporary relief housing and a church for victims of the disaster. The design was further adapted and utilized in 2001 for relief housing in Ahmadabad, India [4], and in 2010 for shelters in Haiti [2]. While suitable for permanent applications, paper tubes have become popular for temporary structures, largely because of their potential inventiveness and minimal environmental impact. The Nomadic Museum by Ban was a traveling temporary exhibition space which featured the photography of Gregory Colbert. The structure combined 152 shipping containers and large paper tubes to create a 56,000 square-foot (5200 square-meter) space [10]. In 2008, architects from the firm WORK Architecture Company transformed the P.S.1 courtyard into an urban farm for their temporary installation [14]. Paper tubes were the primary construction material for this "Public Farm 1", serving as support columns, furniture, and containers for the plants and crops.

The temporary exhibition at MoMA in New York City, and the Hanover pavilion in Germany, were completed by Ban in 2000 [7]. The MoMA exhibition was comprised of long paper trusses spanning 80 feet (24 m). The chords of the trusses were created from 6-in. to 8-in. (150–200 mm) diameter paper tubes of 1-in. (25 mm) wall thickness, while steel rods and cable elements were utilized between the chords to provide stiffening [7]. Ban's design for the Hanover pavilion was a flexible grid shell structure of paper tubes, and covered an area of 27,000 square-feet (2500 square-meters). The goal of the project was to create a structure (using low-tech construction menthols) with the smallest amount of industrial waste possible, and to recycle or reuse all of the construction materials following disassembly [3]. Due to a large amount of creep in

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the paper tubes, a series of wooden ladder arches were constructed and tied into the paper tube grid shell [11]. During construction, the sections of the ladder arches was increased and steel reinforcements were added because city officials required recalculation of the pavilion as a rigid structure as opposed to flexible [11]. In addition to paper tube bending, curved and arch shapes have also been accomplished by joining together small straight segments as seen in the 2007 temporary bridge designed by Ban [6]. Gently arching over the Gardon River in France, the bridge is comprised of 281 recycled paper tubes and utilizes additional metal, wood, and plastics [6].

The case study that follows examines the use of environmentally creep-formed paper tubes for the construction of a large temporary outdoor exhibition titled, *Portals to an Architecture* [15]. The sculpture was designed to have a minimal environmental impact, and exemplify different techniques and methods to design and engineer more sustainably. To that end, paper tubes were chosen as the primary structural material for the exhibition due to their inherent recycled paper content, ability to be recycled into new paper tubes afterwards, and because they are a low-cost material available worldwide.

Following an introduction to the case study, the mechanical and geometrical properties of the paper tubes are described. These properties were integral to the design process and largely informed the geometry of the structure due to the limitations and constraints of the materials, but also resulted in design opportunities throughout the project. An engineering design basis is then presented which applies the mechanical and geometrical properties of the paper tubes and other materials to the design of the structure in order to meet code requirements and ensure public safety. Construction methods and techniques for the final exhibition are then described. Finally, remarks are discussed which relate to the sustainability and environmental impact of temporary structures as well as the need for the engineering of these structures to be integrated throughout the design process.

2. Introduction to the case study

Portals to an Architecture (Fig. 1) was a temporary structure and sculpture constructed at the University of Wisconsin–Madison consisting of an interconnected array of 3–6-in. (75–150 mm) diameter paper tube arches [15]. The sculpture utilized 100% recyclable materials, exemplified sustainable design and construction techniques, and was thoroughly studied and engineered prior to installation and public interaction.

The Portals were constructed on the mall which extends north from the Engineering school, and spanned playfully across the spillway of the existing fountain. The project was then exhibited for the months of May and June in 2006. Afterwards, the entire structure was disassembled and all of the materials were recycled or reused in other projects.

The Portals were designed and constructed to exemplify and demonstrate techniques for combining sculpture, engineering, and systemic sustainability in the form of a temporary structure. There was a special focus on innovative material selection, and sustainability-related decision making. In addition to environmental, the project also addressed social sustainability in that it was a work constructed and exhibited in the public realm, bringing the typically private engineering research project out of the laboratory. As a public art piece, the Portals encouraged interaction and was open to all. Academically, the collaboration of many different individuals, departments, disciplines, local businesses, and industry sponsors allowed for the project to transcend the realm of engineering research into public art as well. In the end, the Portals not only stood alone as a finished work, but exemplified a process.

The proposal to build a temporary structure came from research explorations with paper tubes as a construction material. The idea to use paper tubes demanded an application that was unique and appropriate to the material. Furthermore, to push the limits of the material, the decision was made to focus on applications involving curved tubes which were environmentally creep-formed under their own weight prior to use in the field. In previous arch-like structures built using paper tubes (Hanover, MoMA, etc.), the tubes have been bent in the field. This application is believed to be the first time pre-curved creep-formed paper tubes have been used in a structure.

The structure was designed to exemplify a design process which focused on sustainability and innovation. It was to be 100% recyclable, and have the lowest environmental impact as possible. While sculptural in form, the design could also be the basis for temporary emergency structures needed for disaster relief. The final design was realized as a series of interconnected arches that gave metaphorical form to the internal bone cavities of the first author's

Fig. 1. Image of final exhibition looking towards Engineering Hall.

Fig. 2. X-ray image.

skull, referenced from medical images made during the time when he was under chemotherapy and radiation treatments to cure a lymphoma. Circular segments of various sizes were observed in two-dimensional X-ray images of the skull (Fig. 2). These arches were then arranged in three-dimensional space to give form to the cavities and bone structures of the skull as observed through CT scan imaging. There was a clarity and structural economy evident in these scans, as they were indeed a beautiful architecture based on strict principles of biological engineering.

Table 1
Paper tube ultimate bending stress at 10% moisture content.

Paper tube ID	Wall thickness	Ultimate bending stress at 10% MC
3 in. (75 mm)	0.5 in. (12.7 mm)	1922 psi (13.25 MPa)
4 in. (100 mm)	0.5 in. (12.7 mm)	1727 psi (11.91 MPa)
6 in. (150 mm)	0.6 in. (15.2 mm)	1579 psi (10.89 MPa)

Table 2
Paper tube Modulus of Elasticity (dynamic testing) [5].

Paper tube ID	Wall thickness	Modulus of Elasticity
3.01 in. (76.53 mm)	0.33 in. (8.38 mm)	340,000 psi (2343 MPa)
5.94 in. (150.88 mm)	0.51 in. (13.00 mm)	600,000 psi (4132 MPa)

3. Mechanical and geometrical properties of paper tubes

The bending strengths of the paper tubes were provided by Sonoco Products Company (Hartsville, SC) based on paper tube inner diameters (IDs), wall thickness, moisture content, and the type of paper and manufacturing process utilized (Table 1). Sonoco also provided guidance for the Modulus of Elasticity (300,000 psi (2070 MPa)), density (0.027 lb/in.^{3} (0.75 g/cm^3)), and Poisson's ratio (0.25) for the paper tubes. The value for Modulus of Elasticity was comparable (and slightly conservative) to published data on paper tubes of similar radius and wall thickness as researched by Bank et al. [5] as seen in Table 2.

The preliminary design of the structure was created with the assumption that a number of different paper tube sizes would be utilized. The length of the overall tube (L), inside diameter (ID) of the cross section, outside diameter (OD) of the cross section, and the wall thickness (t) were varied based on the different sizes of the arches and their visual "weights". The arches were designed as circular segments with the preliminary design variables being the overall arch radius and the individual paper tube geometry. Varying the paper tube ID allowed for the minimum arch radius to change. For example, smaller ID tubes were able to bend into tighter radii than tubes with a larger ID. Thus, the preliminary arrangement and size of the arches was based on the minimum radius that each different paper tube ID size could yield.

For an initial approximation to determine what size arches could be made based on the paper tube geometries, beam theory was used. With the initial paper tube material properties, the maximum strain in the material was determined from Eq. (1):

$$\varepsilon_{\max} = \frac{\sigma_{cr}}{E} \tag{1}$$

where $\varepsilon_{\max}$ is the maximum strain; σ_{cr} the critical bending stress (2000 psi (13.8 MPa)) and E is the Modulus of Elasticity (300,000 psi (2070 MPa)).

Relating the overall arch radius (R) and the paper tube diameter (D) (Fig. 3) yields another method to calculate the maximum strain as seen in Eq. (2):

$$\varepsilon_{\max} = \frac{D}{2R} \tag{2}$$

Rearranging Eq. (2) to solve for the minimum arch radius gives:

$$R = \frac{D}{2(\varepsilon_{\max})} \tag{3}$$

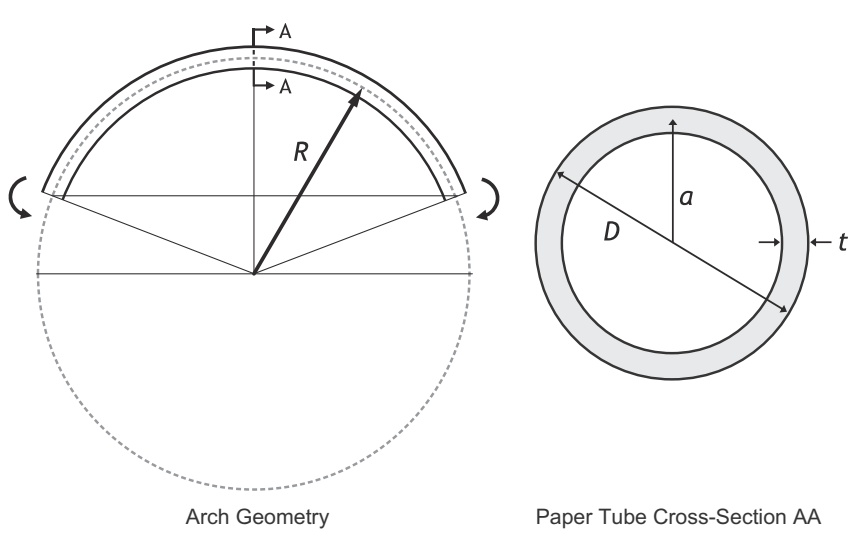

Fig. 3. Paper tube arch and cross section variables.

Using the maximum strain value (0.007 or 0.7%) calculated with Eq. (1), the minimum arch radii were determined based on input of different paper tube ID values. These initial values, as listed in Table 3, represent conservative estimates because the time dependent nature of the bending process was not considered in the calculations. Thus, they were used as a starting point in the process to create a final design.

To check for the possibility of failure due to local wall buckling the critical buckling stress was calculated using Eq. (4) [19] and then converted into a maximum strain with Eq. (6):

$$\sigma_{cr} = \frac{Eh}{a\sqrt{3(1-\nu^2)}} \tag{4}$$

$$\sigma = E\varepsilon \tag{5}$$

$$\varepsilon_{cr} = \frac{h}{a\sqrt{3(1-\nu^2)}} \tag{6}$$

Table 3
Arch radius based on approximate paper tube diameter.

Paper tube OD	Minimum arch radius
3 in. (76.2 mm)	17.86 ft (5.44 m)
4 in. (101.6 mm)	23.81 ft (7.26 m)
5 in. (127.0 mm)	29.76 ft (9.07 m)
6 in. (152.4 mm)	35.71 ft (10.88 m)
7 in. (177.8 mm)	41.67 ft (12.70 m)
8 in. (203.2 mm)	47.62 ft (14.51 m)
9 in. (228.6 mm)	53.57 ft (16.33 m)
10 in. (254.0 mm)	59.52 ft (18.14 m)

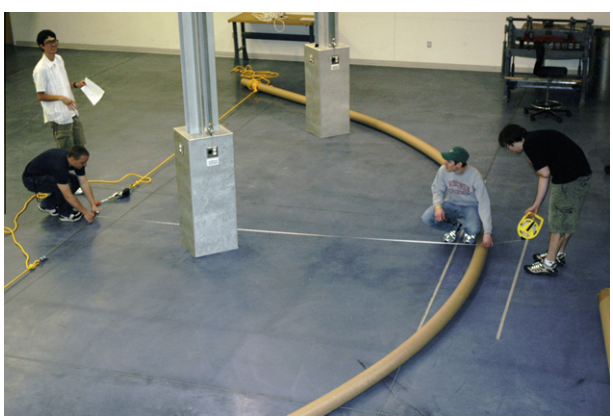

Fig. 4. Physical test performed to observe bending in actual paper tube.

where h is the paper tube wall thickness, inches; a the radial distance from tube center to tube wall (see Fig. 3), inches; ν the Poisson's ratio and ε_{cr} is the critical buckling strain, in./in.

Based on calculations for a 6-in. ID (150 mm) tube with a wall thickness of 0.5 in. (12.7 mm), the critical buckling stress (27,500 psi (190 MPa)) was found to be much larger than the paper tube strength (1580 psi (10.9 MPa)). The critical buckling strain (9%) was also much larger than the critical strain (0.7%). Based on these calculations, failure due to bending would occur long before failure due to buckling.

The design for the individual arches was based upon the geometry of circular segments. Physical bending tests were performed to observe the tubes and better understand the variability of the arch shape (Fig. 4). The precise mathematic variables for circular arch geometry (Fig. 5) were calculated as follows:

Eqs. (7)–(12) relate these variables mathematically to one another:

$$s = r\theta \tag{7}$$

$$s = \frac{r\theta\pi}{180} \tag{8}$$

$$c = 2\sqrt{r^2 - d^2} \tag{9}$$

$$c = 2\sqrt{h(2r-h)} \tag{10}$$

$$d = \frac{\sqrt{4r^2 - c^2}}{2} \tag{11}$$

$$d = \frac{c\cot(\theta/2)}{2} \tag{12}$$

where s is the arc length, feet; r the radius of circle, feet; θ the angle, radians; c the chord, feet; d the apothem (distance from chord to center circle), feet and h is the height from chord, feet.

While designing the individual arches, it was often times convenient to consider a given arc length and height, and to then compute the remaining geometric values. Eq. (13) relates circular arc length and height from the chord of an arch:

$$\frac{2h}{s} = \frac{(1-\cos(x))}{x} \tag{13}$$

where x is the unknown variable.

Newton's method is required to solve for the unknown variable 'x' (Eqs. (14)–(16)):

$$k = \frac{(1-\cos(x))}{x} \tag{14}$$

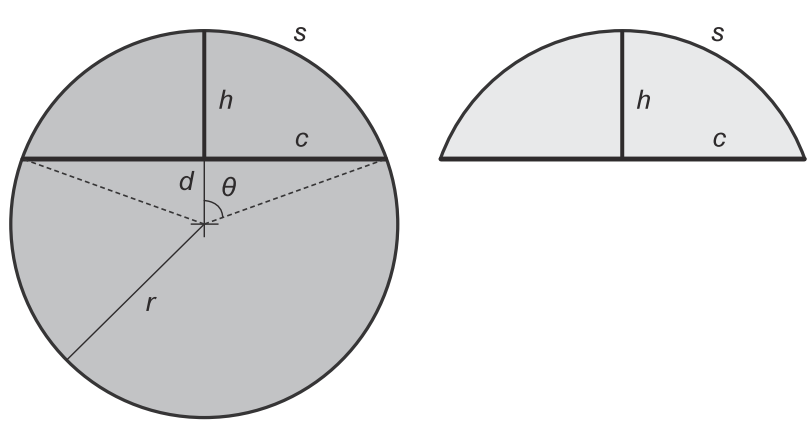

Fig. 5. Geometric arch variables.

$$k = 2\frac{h}{s} \tag{15}$$

$$x(n+1) = x(n) - \frac{(\cos[x(n)] + kn(n) - 1)}{(-\sin[x(n)] + k)} \tag{16}$$

Following the use of Newton's method when 'x' is known, Eqs. (17)–(20) were then used to relate the following geometric variables:

$$\theta = 2x \tag{17}$$

$$c = 2r\sin(x) \tag{18}$$

$$r = \frac{s}{\theta} \tag{19}$$

$$d = r - h. \tag{20}$$

4. Design basis

An engineering design basis according to the allowable stress design (ASD) philosophy was used. Based on the type of structure and the duration of the exhibition, the safety factor was set at 1.5. Since the paper tube structure shared similar characteristics to skeletal-like structures composed of thin members connected together, the loads and load combinations analyzed for the structure were based on the Standard Specification for Structural Supports of Highway Signs, Luminaires and Traffic Signals [1]. Table 4 lists the AASHTO group load combinations:

Group load case II was found to govern for the project.

In order to be able to construct and easily dissemble the structure, simple connection details were sought during the design process. Strongwell Fibrebolts [18], which consist of pultruded fiberglass studs (treaded rods) and thermoplastic nuts, were utilized for all connections. Being non-metallic, the Fibrebolts were non-corrosive as well as extremely lightweight. In addition, they were very high strength and available in many different sizes. Most importantly, the Fibrebolts were a sustainable choice when their life-cycle and required energy inputs were compared with galvanized and stainless steel bolts. An agreement was also established that allowed for the return and reuse of the nuts to Strongwell following the exhibition.

Once the preliminary design was complete, a model for structural analysis was created using the structural analysis software program Visual Analysis [20]. The ends of the arches were modeled as fixed connections, while the tube members were modeled as "pipe" elements (Fig. 6). The following properties were inputted for the paper tubes and Fibrebolt connecting elements (which linked the arches together at their crossings):

Paper tubes:
- E = 300,000 psi (2070 MPa),
- ν = 0.25,
- α = 1.00 in./in./deg-F,
- ρ = 0.027 lb/in.^{3} (0.75 g/cm^3).

¾″ Fibrebolt:
- $E = 2.5 \times 10^6$ psi (17.24×10^3 MPa),
- ν = 0.20,
- $\alpha = 5.00 \times 10^{-6}$ in./in./deg-F,
- ρ = 0.06 lb/in.^{3} (1.66 g/cm^3).

½″ Fibrebolt:
- $E = 2.0 \times 10^6$ psi (13.79×10^3 MPa),
- ν = 0.20,
- $\alpha = 5.00 \times 10^{-6}$ in./in./deg-F,
- ρ = 0.06 lb/in^3 (1.66 g/cm^3).

Following the modeling of the arches and assignment of material properties, the loadings due to wind were added. In order to best represent the direction of highest wind speed the structure was likely to be subjected to, the average wind direction was calculated for the previous 6 years using data from the University of Wisconsin's Atmospheric and Oceanic Sciences department weather database, which is recorded very near the site. The average wind direction was found to be 102° counter-clockwise from north, and the load was applied to each arch of the Visual Analysis model in the negative-x direction representing a gust from predominantly west to east.

After applying the wind loading, a P-Delta type analysis of the structure was performed. The deflected shape of the structure can be seen in Fig. 6. A statics check was then successfully performed, yielding a percent error of just 0.0076%. The internal forces and stresses in the members were then investigated. For this analysis, all of the pipe elements representing the paper tube arches were selected and the values tabulated based on the inner diameter of the tubes.

Eq. (21) was used to find the maximum stresses in the members after the internal bending moments had been extracted from the analysis (Fig. 7).

$$\sigma_{\max} = \frac{My}{I} \tag{21}$$

where $\sigma_{\max}$ is the maximum stress, psi; M the bending moment, lb-in.; y the distance from centroid to extreme fiber, inches and I is the moment of inertia, in.^{4}.

As seen in Table 5, the maximum bending stresses in the structure were lower than the ultimate bending strengths (including 133% of allowable stress). Biaxial bending was also checked for each member. Four arch ends showed a biaxial bending ratio slightly greater than one while the rest of the structure was fine. Modeling the structure with fixed ends caused these high stresses. The actual arches, however, were not fully fixed, but rather maintained some characteristics of a pinned connection. Thus, these

Table 4
AASHTO group load combinations.

Group load	Load combination	Percent of allowable stress
I	DL	100
II	DL + W	133
III	DL + ice + 1/2 W	133
IV	Fatigue	–

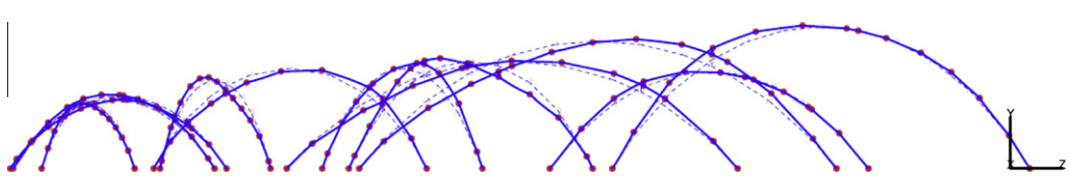

Fig. 6. Side view of the deflected shape looking west (deflection factor = 0.1).

areas of slightly higher stress were an outcome from the type of modeling and analysis.

Load deformation response and likely failure mode was observed by bending a 53-foot long tube to failure (Fig. 8). The failure mode was found to be tearing of the material in tension at the ply winding angle of the exterior surface during extreme bending (Fig. 9). Compression wrinkling along the inside surface of the arch were also observed as the arch neared failure. Since the individual arches were designed as a function of the radius of curvature and the diameter of the tube, the loads required for failure were thus far beyond what we expected the structure to see during bending, construction and exhibition.

The Portals were an open structure designed within the structural limitation of the materials utilized. The risk of arches tipping

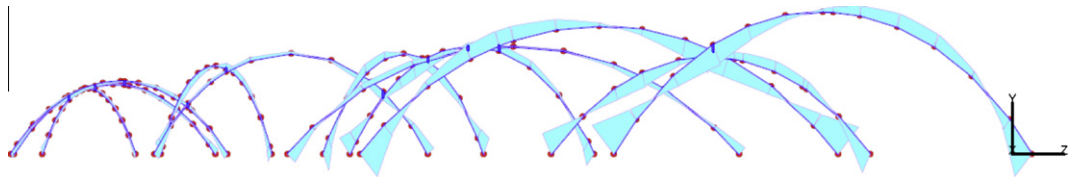

Fig. 7. Bending moment diagram (*Z* direction) looking west.

Table 5
Maximum stresses compared with ultimate stresses.

Paper tube geometry					Ultimate strengths		Maximum stresses				
ID (in.)	OD (in.)	*t* (in.)	*y* (in)	*I* (in.^{4})	Ultimate bending strength (10% MC) (psi)	Ultimate bending strength/factor of safety (1.5) (psi)	fa (psi)	fby(+z) (psi)	fby(−z) (psi)	fbz(+y) (psi)	fbz(−y) (psi)
3	4	0.5	2	8.42	1922	1281	−60	410	−410	1270	−1270
4	5	0.5	2.5	17.89	1727	1151	−90	−610	610	−1060	1060
6	7.2	0.6	3.6	67.74	1579	1053	−40	−980	980	−790	790

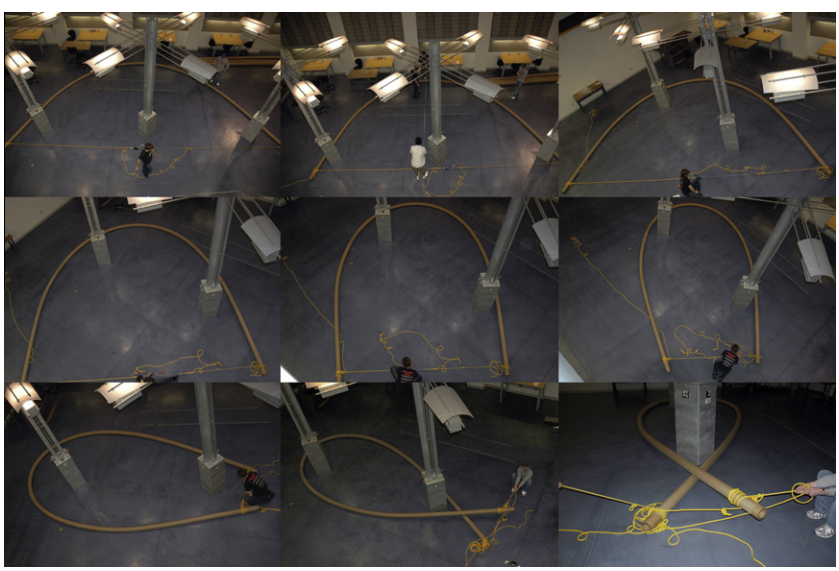

Fig. 8. Bending test of a 53-foot long paper tube arch.

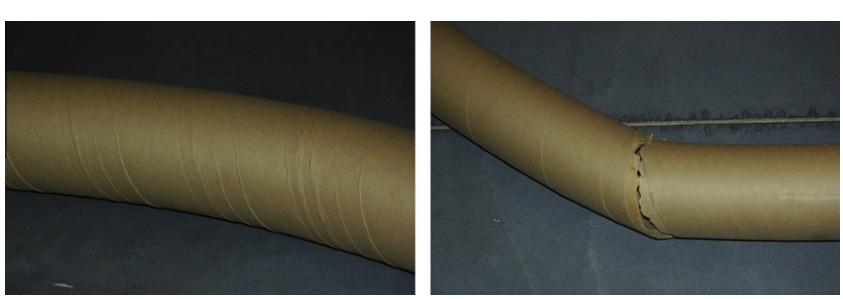

Fig. 9. Compression wrinkling (left), failure of the paper tube in tension (right).

over during installation was identified and minimized during the construction process by stabilizing each tube with ropes, and immediately backfilling the foundation holes prior to the structure being fully connected. Additional precautions were taken to determine if persons hanging from the structure would cause damage or failure to individual arches and the structure throughout the construction process and exhibition. Individual load cases with point loads acting as such forces were analyzed, and resulted in stresses much lower that those calculated from the dominant wind load cases.

5. Constructing the Portals

Planning and construction of the Portals was assisted by nine freshman students who collaborated on the project in conjunction with an Introduction to Engineering course. They participated throughout the entire spring 2006 semester, with special focus on sustainability, preparation for construction, and actual building of the project.

The paper tubes for the project were manufactured during the last week of March 2006 in Hartsville, SC by Sonoco. They were cut to a length of 53 feet (16.15 m) in order to fit into a standard semi-truck trailer, and were given a slight pre-bend (camber) to initiate bending. To create the pre-bend, straight tubes were stacked atop two large support boxes which caused the tubes to arch under their own weight. The pre-bend took place after the adhesive binding the paper tube plies was dry, but before it fully cured. The paper tubes left Hartsville with a moisture content of 12%, and arrived in Madison, WI with a moisture content around 10% – a value estimated based on travel time and the rate of dissipation. To prevent further loss of moisture, the ends of the tubes, where a majority of the moisture is transferred, were sealed with multiple coats of low-VOC polyurethane upon arrival. Large pedestal-like supports were constructed to hold the paper tubes, and to provide a means for allowing them to creep into their desired shape over a period of 3 weeks (Fig. 10). The tubes were supported at four points which were incrementally raised every few days until each tube reached its proper curvature. Over the course of the bending process, the shape of the tubes was checked and confirmed by measurements taken to determine the height of each arch at various lengths along their chords. Towards the end of the bending process, additional force was applied to ends of the arches because the self-weight of the tubes themselves was not sufficient to form the correct curvature through creep of the material alone.

Since some of the arches were designed to be longer than the shippable length of 53 feet (16.15 m), tube-to-tube connections were created to achieve the full arc length required (Fig. 11). Each of the 4-in. (100 mm) and 6-in. (150 mm) ID arches required this connection. While the tube-to-tube connections were visible in the 6-in. (150 mm) ID arches, they were hidden from view in the 4-in. (100 mm) ID arches, because the arc lengths of the these tubes were just slightly above 53 feet (16.15 m). Thus, instead of splicing two arches together at the center, additional length was added to each end, which was then concealed inside the arch foundation. Being significantly longer than 53 feet, the 6-in. (150 mm) ID arches required a connection which utilized a tight fitting interior paper tube that was secured in place with four Fibrebolts.

Knowing that the tubes would be subject to different weather conditions once constructed outside on the Engineering Mall (Fig. 12), different weatherproofing methods were investigated. While the sun's UV rays were a possible form of damage, the main priority was to keep the tubes dry, as paper tubes are very sensitive to changes in moisture content. When a paper tube increases in moisture content just 1%, the tube sees a loss of strength around 10% [7]. Thus, providing protection from the rain and other conditions that would cause an increase in moisture content was very important for the success of the project. A simple defense against moisture was already present in each tube upon arrival. A special moisture barrier ply was wound in each paper tube below the first few paper layers. This waxy layer prevented moisture from permeating deep into the wall of the paper tube. While the first few outside plies could become saturated with moisture during rain, it would stop at the moisture barrier, and not penetrate further.

A second method to prevent damage caused by rain and moisture was to coat the paper tubes with an exterior weatherproofing

Fig. 11. Students constructing tube-to-tube connections.

Fig. 10. Paper tubes being formed into shape atop pedestal supports.

Fig. 12. Heavy rains fall during the exhibition opening week.

layer. Different coating methods and products were tested on sample paper tubes. It was found that applying multiple layers of a low volatile organic compound (VOC) polyurethane provided the best protection, nicest finish, and was the most environmentally friendly. The actual coating of the tubes took place after they had been formed into their final shape. Each arch had two thin layers of urethane coating applied before leaving the lab for construction of the exhibition.

The Portals were constructed in four afternoons during the last 2 weeks of April 2006. The site was first prepared by marking information such as the location of each arch and the connections between arches onto the ground plane. Foundation holes were then dug where the arches were anchored into the ground (Fig. 13). Approximately 20% of the total arc length of the paper tube was underground. This dimension, which varied from arch to arch, determined the depth and size of each corresponding foundation hole. When the two foundation holes for a given arch were excavated, the paper tube to be installed was cut, or elongated with an arch-to-arch connection, to its precise dimensions. The arch was then walked over from the lab to the Engineering Mall, and placed on its side with its ends close to the foundation holes.

While waterproofing each entire tube was important, it was particularly critical to keep the below ground foundation system water tight. If simply placed in the ground, the ends of the arches would have been subject to infiltrating rain water, ground water, and general soil moisture. To protect the ends of the paper tube arches, foundations were designed using high density polyethylene (HDPE) culvert pipe sections. The dual-walled, HDPE pipe had advantages over the use of polyvinyl chloride (PVC) and other foundation material types. First, the dual-walled HDPE pipes were both light weight, strong, and could be fitted with an end cap. They were delivered in 20-foot (6.1 m) long sections and were easy to cut to the correct length. The pipes protected the tubes as the foundation holes were backfilled and compacted. Also, the HDPE pipe was corrugated, or ribbed, allowing additional friction and anchoring in the soil. The extra grip with the soil helped prevent the tubes from pulling out of the ground during an updraft of wind. In addition, the HDPE pipes were made of recycled content, and were reused in further research through the Geotechnical Engineering program following the exhibition.

HDPE culvert pipe of 6-in. (150 mm) and 10-in. (250 mm) diameter were utilized for the exhibition. The 6-in. (150 mm) pipes was used for the 3-in. (75 mm) and 4-in. (100 mm) ID arches, while 10-in. (250 mm) diameter was used for the 6-in. (150 mm) ID arches. A larger diameter culvert tube size was selected to accommodate the slight arch bend present in the paper tubes. Also, the space between the culvert pipe and paper tube allowed for placement of dry sand to help anchor the foundation ends and to serve as an additional back-up method to keep moisture away from the paper tube ends.

With the culvert sleeves in place, the arch was then carefully inserted into foundation holes and lifted into place (Fig. 13). No additional pre-load was required because the foundation holes were dug large enough so that the arches could be lowered into position without needing additional force to make them fit. Once the ends were in the foundation holes, the arch was then moved into its correct position by field measurements of the height and arch chord distance. Once correctly positioned, the culvert sleeves were filled with the dry sand. Finally, a plastic flashing was installed where the paper tube interfaced the top end of the culvert pipe.

The arches were placed from the south end of the Engineering Mall towards the north end, starting with the 3-in. (75 mm) ID tubes, and followed by the 4-in. (100 mm) and 6-in. (150 mm) ID tubes. To facilitate construction, the taller arches were placed first where possible. Each arch was connected to at least one other so that they could work together to form a complete and stable structure. Fibrebolts were used for these eleven arch-to-arch connections and installed on site utilizing two Fibrebolt nuts, a length of threaded Fibrebolt rod, and rubber washers for sealing (Fig. 14). When the arches were in-place outside, two additional thin coats of urethane were applied (Fig. 15). Similarly, after the individual connections were made between the arches, the areas were coated with urethane for weatherproofing.

The Portals were exhibited on the Engineering Mall for 2 months (Fig. 16), through which they were subjected to heavy

Fig. 13. Foundation hole and culvert sleeve receiving the paper tube arch end.

Fig. 14. Arch-to-arch connection (left), tube-to-tube connection (right).

Fig. 15. Applying an additional layer of urethane.

Fig. 16. View of final exhibition looking north.

late spring rains and large amounts of solar radiation during the summer heat. Due to the predominantly fixed foundation conditions and the arch-to-arch connections throughout the sculpture, very little creep was observed over the duration of the exhibition. The paper tubes held up very well, with only some noticeable lightening of color. During heavy extended rains, wet spots were occasionally prone to appear where microcracks in the urethane had occurred. Theses spots dried quickly, as they were found only in the few plies of paper beyond of the waxy moisture barrier layer wound into the tubes.

6. Dissassembly and Recycling

All the paper tubes used for the exhibition and for research and testing were recycled into new paper products at Sonoco's Menasha, Wisconsin facility (Fig. 17). The Fibrebolt nuts were sent back to Strongwell to be reused while the threaded rod was given to the composites testing lab for future research projects. Some of the HDPE culvert pipes were donated to the Geotechnical Engineering program for use in future research projects, while the rest were recycled. The plywood and lumber used to construct the bending supports were disassembled, and donated to the Structures and Materials Testing Laboratory for future use in research projects.

In addition, all purchased construction materials and tools were donated to Introduction to Engineering course labs. Through the recycling and reusing initiatives, the project set an example as how to manage a large student project with minimal environmental impact. This reduction was accomplished by carefully evaluated and challenging each decision in terms of sustainability throughout the entire project duration.

Fig. 17. Following take-down, the Portals awaiting pick-up for recycling.

Temporary structures if not recycled, contribute significantly to the growing amount of construction waste. Planning for their afterlife should occur during the design process, and temporary structures should be recycled or reassembled completely so they do not end up in a landfill after a single use. This loop of resource recycling and reuse is known as "cradle to cradle" design, and is championed by American designer William McDonough and German chemist Michael Braungart [12]. Beyond choosing reusable and recyclable materials, details and components of the structure can be designed for easy disassembly and reassembly, while methods can be developed to foster further uses of the structure. Considering the environmental impact of each decision during the design process is important in regards to the overall sustainability of the project. Life Cycle Assessment is an important technique that involves assessing the environmental impact of a project by first tabulating the relevant energy and material inputs, and the environmental consequences of the project. These impacts are then evaluated, and the results are used to make more informed decisions regarding the sustainability of the project [9].

7. Conclusions

Engineering and sustainable features of temporary structures need to be considered as an integral part of the design process beginning at the conceptual phase. In the author's opinion, engineering studies to analyze these structures should be as important as the overall artistic and architectural vision. When successfully integrated, the fusion of the artistic and the technical can result in a holistic design transparency wherein the architecture and the engineering become one and the same. Public safety is the most important reason for engineering analysis of temporary structures. The safety of structures cannot simply be checked at the end of the design process, but must be fully integrated throughout in order to be most effective. Understanding and addressing engineering challenges during the design process allows for a safer structure, and includes the means for prevention of accidents as well. Due to the ephemeral nature of temporary structures, safety standards are often reduced, as perceived risk is lower because of the duration/life of the structure is a fraction of that of a building.

While engineering can be considered an added requirement for the design of temporary structures, it can contribute positively in ways that go beyond its technical nature. Certain engineering constraints, for example, can result in design opportunities which may not have presented themselves before such analysis. Engineering analysis is thus a tool that can improve methods of construction, and reduce the environmental impact of building projects.

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References

[1] American association of state highway and transportation officials (AASHTO). Standard specifications for structural supports for highway signs, Luminaires and traffic signals. 4th ed. Washington DC: AASHTO; 2001.
[2] Ban Shigeru. Disaster Relief in Haiti. Shigeru Ban Architects Web 03 November 2010. <http://www.shigerubanarchitects.com/SBA_NEWS/SBA_news_4.htm>.
[3] Ban Shigeru. Japan Pavilion, Expo 2000 Hanover, Germany, 2000. Shigeru Ban Architects Web 25 October 2010. <http://www.shigerubanarchitects.com/SBA_WORKS/SBA_PAPER/SBA_PAPER_10/SBA_paper_10.html>.
[4] Ban S, Shodhan K. Paper-tube housing. The MIT press on behalf of perspecta, vol. 34; 2003. p. 154–5, 158–9 [Print].
[5] Bank LC, Cofie E, Gerhardt TD. A new test method for the determination of the flexural modulus of spirally wound paper tubes. J Eng Mater Technol 1992;114:84–9 [Print].
[6] Chapa Jorge. Cardboard bridge by Shigeru Ban. Green design will save the world|inhabitat. Inhabitat 7 August 2007. Web 25 October 2010. <http://inhabitat.com/2007/08/07/shigeru-bans-cardboard-bridge/>.
[7] Correa Cristobal. Designing with paper tubes. Struct Eng Int 2004; 277–81 [Print].
[8] Gerhardt TD, Qiu YP, Wang Y, Johnson CG McCarthy M, Rhodes DE. Engineering paper tubes to improve winding performance. mechanics of cellulosic materials. ASME Joint Applied Mechanics and Materials Division Meeting Blacksburg, VA, USA; June 27–30 1999. p. 159–76 [Print].
[9] Life Cycle Assessment (LCA). US Environmental Protection Agency. 6 August 2010. Web 3 November 2010. <http://www.epa.gov/nrmrl/lcaccess/>.
[10] Lubell Sam. Ban's nomadic museum opens in Santa Monica. Architectural record 2 February 2006. Web 25 October 2010. <http://archrecord.construction.com/news/daily/archives/060202ban.asp>.
[11] Lyall, Sutherland. Remarkable structures: engineering today's innovative buildings. New York: Princeton Architectural Press; 2002 [Print].
[12] McDonough William, Michael Braungart. Cradle to cradle: remaking the way we make things. New York: North Point; 2002 [Print].
[13] McQuaid Matilda, Ban Shigeru. New York: Phaidon Press Limited; 2003 [Print].
[14] Pogrebin Robin. Betting a farm would work in queens. New York Times; 7 February 2008 [Print].
[15] Preston Steven J. Portals to an architecture. MS thesis. University of Wisconsin, Madison; 2006 [Print].
[16] Sonoco. Construction. Sonoco. Sonoco Products Company. Web 25 October 2010. <http://sonoco.com/productsservices/tubescores/construction.aspx>.
[17] Sonoco. Tubes & Cores. Sonoco. Sonoco Products Company. Web 25 October 2010. <http://sonoco.com/productsservices/tubescores.aspx>.
[18] Strongwell. Fibrebolt. Fibrebolt. Strongwell. Web 03 November 2010. <http://www.strongwell.com/products/pultruded_prod/studs_nuts/index.shtml>.
[19] Timoshenko SP, Gere JM. The theory of elastic stability. New York: McGraw-Hill; 1961 [Print].
[20] Visual Analysis. Vers. 5.5. Bozeman, MT: Integrated engineering software; 2006. Computer software.