

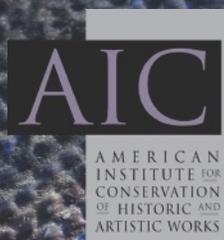
The AIC Paintings Specialty Group

POSTPRINTS

VOLUME TWENTY-SIX 2013

Papers Presented at the 41st Annual Meeting of the
American Institute for Conservation of Historic and Artistic Works
Indianapolis, Indiana May 29-June 1, 2013

Compiled by Barbara Buckley



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AIC PAINTINGS SPECIALTY GROUP

POSTPRINTS
VOLUME 26 2013 ANNUAL MEETING

*Papers Presented at the 41st Annual Meeting of the American Institute for Conservation of Historic and Artistic Works
Indianapolis, Indiana May 29–June 1, 2013*

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Modernized Stretcher for Paintings on Canvas: Assessment and Observation

ABSTRACT

A new aluminum stretcher that does not employ conventional keys, expansion bolts, or springs for tension adjustment has been developed. The tension adjustment is achieved by moving the stretcher bars in each direction independently by turning thumbscrews positioned along the stretcher. This stretcher can be used to strengthen an existing stretcher or as an artist-grade stretcher. Its construction and mechanical properties were analyzed and compared with traditional wooden stretchers with keys to examine craquelure patterns incurred on the canvas and assess any deformation resulting from the two stretcher systems. Expansion by means of movable aluminum bars has greater impact at the center of the canvas and does not bend the stretcher. Further research is required to gain a better understanding of mechanical stresses resulting from expansion and methods of tension adjustment.

1. INTRODUCTION

In his seminal 1969 work on mechanical stress on paint film (1969), S. Keck classified agents that cause a painting to deteriorate as chemical, physical, and biological. These agents generate mechanical stress on paint film that lead to cracking and eventual flaking of the paint. In this investigation, the authors focused on external mechanical stress created by stretcher expansion in an environment with fluctuating relative humidity (RH) that results in aging cracks, and not on internal mechanical stress cracks, or drying cracks, created by incorrect painting technique and/or faulty material. A functional stretcher that has a mechanism for adjusting tension provides a painting on canvas with dimensional stability, without creating undue stress to the painting. Stretchers with expandable joints appeared in the mid-18th century with the introduction of a stretcher key (Buckley 2008). Since 1793, thousands of patents have been issued by the United States Patent Office for stretcher designs and the machinery to produce them (Buckley 2008, AIC Wiki 2007). For two centuries, however, the basic concept of adjusting tension has remained unchanged: opening the corner joints by keying-out, a process of forcing a stretcher key into a mitered corner joint, causing stress via interdependent biaxial expansion (simultaneously between the x and y axes).

Keying-out is typically performed by expanding the stretcher at the corners with wooden wedges, expansion bolts, or springs. If this is done unnecessarily, incorrectly, or ineffectively,

the excess stress on the canvas can be transmitted to the paint film, resulting in cracking, cupping, cleavage, and flaking in the paint, or even tears in the canvas. This damage may not be immediately evident, but will become obvious over time. Keying-out can correct loose canvas in smaller paintings but is not recommended for large-format paintings. Slackened canvas in a large-format, vertically hung painting usually results in a bulge in the lower part of the painting that cannot be easily resolved by keying-out (Canadian Conservation Institute 1993). The painting must be dismantled and restretched to achieve its original tautness. Still, while keying-out is not recommended as a routine procedure, it is still commonly used as a means of tension adjustment in the conservation and art communities.

In the latter half of the 20th century, conservators attempted to design a stretcher that would address the problems inherent in traditional keyed stretchers. They created different kinds of joint-adjusting mechanisms, including the ICA spring stretcher and expansion-bolt stretcher (AIC Wiki 2007), but these systems were still grounded in biaxial interdependent expansion.

Physically and chemically inert support materials, such as aluminum, have been investigated as alternatives to wood since 1941 (AIC Wiki 2007). Metal stretchers provide dimensional stability and do not react to changes in relative humidity as wooden stretchers do. Metal stretchers are often used as conservation-grade supports (Buckley 2012), but the higher

cost of material, labor, and fabrication compared with wooden stretchers limits their availability.

The aim of this investigation was to research and design an aluminum mechanism as an alternative to traditional keying-out for tension adjustment. Observational analyses of strain compared the deformation incurred by the new stretcher's independent dimensional expansion with the deformation incurred by the traditional keyed stretcher's interdependent dimensional expansion.

2. BACKGROUND

Volume 2 of the *Painting Conservation Catalog*, "Stretchers and strainers," published in 2007 by the American Institute of Conservation (AIC) Paintings Specialty Group, is one of the most comprehensive works to date on stretchers and strainers. This monumental work, compiled by Barbara A. Buckley, was the result of the volunteer efforts of 43 authors and 12 editorial boards. Available from AIC to conservators, museum professionals, and the public in both online (*AIC Wiki* 2007) and print versions (Buckley 2008), this publication includes valuable historical and technical information on materials, design, and applications, and provided the foundation for this current investigation. However, it does not cover the mechanical alteration of painting composites resulting from stretchers and methods of expansion. This is understandable, given that historical data on the mechanical analysis of wooden stretchers are almost nonexistent. Even today, discussions of the design, material, and function of stretchers are mostly limited to the craft and conservation sphere and rarely involve scientific mechanical evaluation. A rare exception is a work by G. A. Berger published in 1984 (Berger 1984), in which he assesses the mechanical properties of his "self-adjusting continuous tension stretcher;" however, it contains no analysis of mechanical behavior.

A painting on canvas is a composite structure composed of a paint film (from the bottom up, the layers are size, ground, paint, and varnish), fabric (primary support) and a stretcher or strainer (secondary or auxiliary support). Stress on the paint film and fabric increases in response to a decrease in temperature or RH, and to the canvas being restrained by a stretcher or strainer. Works by Hedley (1988), Young and Hibberd (1999), Mecklenburg and Tumosa (1991), and Michalski (1991) provided valuable theoretical models and experimental data on the mechanical behavior of canvas paintings and the results of stress and strain on a painting's composite structure. A. Karpowicz's study of paint cracks (1990) and personal communication with Karpowicz in 2013 provided essential understanding of humidity-induced movement on biaxially stretched fabric. In the last 20 years, mechanical evaluation of stretchers and strainers by conservators

has been rare. Most newly developed stretchers are produced commercially (Alustrech; Simon Liu Inc.; Jackson's Art Supplies; Rex Art) and rely on tension adjustment through interdependent biaxial expansion of the corner joints. Conservators have sought a solution to the constraints of two-dimensional expansion through independent unidimensional expansion for tension adjustment; however, very little comparative analysis of the mechanical properties of interdependent biaxial expansion (traditional keying-out; expansion with turnbuckle bolts) and independent biaxial expansion has been done, other than the work of S. Philips et al.

2.1 Independent Dimensional Expansion Models to Date

In the past, conservators and craftsmen have tried to solve the problems inherent in keying-out systems that rely on interdependent biaxial expansion by redesigning the stretcher to make it capable of independent dimensional expansion. A search of the literature revealed that at least four stretcher systems have been developed that use independent dimensional expansion.

The first model was designed in the United States by H. Holly in 1873 (Katlan 1992). In his patent entitled "Improvement in Canvas Stretching and Protecting Frames," he described his invention as having a bar made from a thin, flat sheet of metal "[that] is moved from or toward said fixed end." In the 1950s, R. Carita designed an expansion system that used springs to move the stretcher along the vertical or horizontal axis, instead of relying on biaxial expansion at the corners. M. Ciatti (2000) and A. Idelson (2009) have made improvements to Carita's system in the last few years. Ciatti's system applies constant, controlled tension through the use of rigid materials such as steel and aluminum. Tension is adjusted by means of purpose-built stainless steel springs that are tightened or released by a nut attached to an aluminum strip. In 1984, Berger published an account of his new stretcher system (1984), which he described as a "self-adjusting continuous-tension stretcher" with a horizontal movable part at the top, connected to a rigid frame with springs that enable unidirectional movement. Finally, on June 5, 1992, Philips presented his design for a new expansion stretcher at the Annual Meeting of the AIC Paintings Specialty Group (Philips 1992). As a way to deal with the "unsolved problem of keying-out canvas expansion," Philips abandoned the miter as the focal point of expansion. Instead, he devised a neutral pivot that allows each bar to move independently in one direction without disturbing the others.

Together, these four expansion systems represent an evolutionary approach to the problems presented by interdependent dimensional expansion and the first important design concepts in independent dimensional expansion, which is the basis of this current investigation.

2.2 Metal Stretchers

To prevent the deformation of wooden frames that results from relative-humidity fluctuation, stretcher bars made from metal began to appear in 1941 (Buckley 2012). The first aluminum stretcher was made by F. Rigamonti in 1966 (AIC Wiki, 2007). Starofix North America, founded in 1984, produces lightweight aluminum stretchers (AIC Wiki, 2007) and Alustretch, based in Vienna, has been a leading manufacturer of aluminum stretchers in Europe since 1990. P. Raich designed a new stretcher for Alustretch as recently as 2008 (Alustrech). A metal stretcher provides dimensional stability, especially for a large canvas, and, unlike a wooden stretcher, does not react to relative-humidity changes. Yet despite their advantages, metal stretchers are less commonly used and not as readily available as wooden stretchers because of the higher costs of material and production, as well as aesthetic concerns.

2.3 The *TWP*² Stretcher

The *TWP*² stretcher takes its name from the initials of its designers: Tsang (a paintings conservator), Williams (a furniture conservator), Pelasara (a master cabinet maker), and Patterson (a metal fabricator). This new stretcher was invented by applying the principle of independent dimensional expansion to a newly designed aluminum stretcher that expands a canvas by turning steel thumbscrews attached to the stretcher bar. The design sprang from failed attempts to correct a distorted canvas by the standard methods of moisture, heat, and/or pressure. The team designed a prototype of the *TWP*² as an insert to strengthen the original stretcher bar. They fitted the insert to the original stretcher, and the resulting tension adjustment was successful. The distortion in the canvas was instantaneously corrected simply by turning the thumbscrews on the expansion stretcher.

The prototype *TWP*² went through five successive design modifications and improvements. The latest model (prototype #5) is made of aluminum, rigid High density polyethylene, or Delrin, and has thumbscrews for tension adjustment positioned along the stretcher bar rather than at the corners of the frame. This stretcher can be inserted as an adjunct to an existing stretcher or used alone as an artist-grade stretcher. Tsang and Madruga (an engineer and paintings conservator) designed experiments to measure stresses and strains on the canvas, as well as craquelure patterns induced by the new stretcher. Budget and time constraints required them to rely on small test samples, visual observation, and simple tools to evaluate the new stretcher system. Eight painting samples coated with glue and gesso were exposed to relative humidity that cycled from 0% to 100% for 14 rounds over six months. Madruga compared the mechanical behavior of the new stretcher with that of a traditional wooden keyed stretcher and evaluated theoretical models of the strain on canvas induced by both systems. This report is the result of one year of product design evaluation and fabrication, and an additional year of mechanical behavior

analysis. Since then, design and evaluation of the *TWP*² has focused on bending of the traditional wooden stretcher bar and other problems inherent to the conservation of canvas paintings. The observations and measurements so far derived from such a small test sample have led to valuable insights; however, a larger test sample and more precise equipment for measuring relative humidity and exact changes in tension over longer periods of time will be required to make further advances in research and design.

3. THE *TWP*² STRETCHER: MATERIALS AND CONSTRUCTION

The *TWP*² stretcher is designed for use as both an artist-grade stretcher and as an insert to strengthen and provide tension adjustment for an existing stretcher. The name *TWP*² applies to both systems, which share common features, construction methods, and mechanisms. For clarity within this report, the insert stretcher is referred to as the *TWP*² insert (fig. 1) and the artist-grade stretcher is referred to as the *TWP*² artist-grade (fig. 2).

The *TWP*² is composed of (1) a U-channel, T-bar, and Z-bar made of commercial-grade aluminum, (2) metal fasteners, including stainless steel threaded thumbscrews and spring pins and aluminum L-plates, and (3) rigid HDPE polyethylene or black Delrin[®] resin strips (fig. 3). The *TWP*² artist-grade also has a wooden tacking edge for stretching a new canvas. This tacking edge, made from basswood, fir, or poplar, is connected to the moveable aluminum T-bar. (See Materials and fig. 23.)

The *TWP*² has rigid aluminum parts that can be cut to size and configured as needed. A rigid inner U-channel is fitted

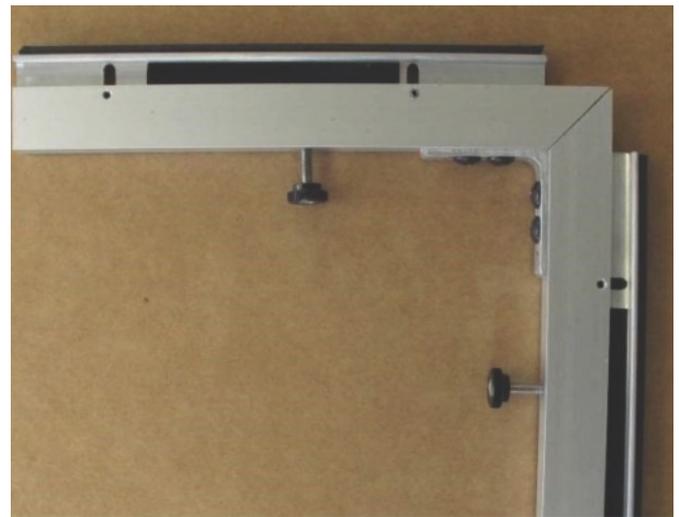


Figure 1. *TWP*² insert, corner detail



Figure 2. *TWP*² artist-grade, corner detail

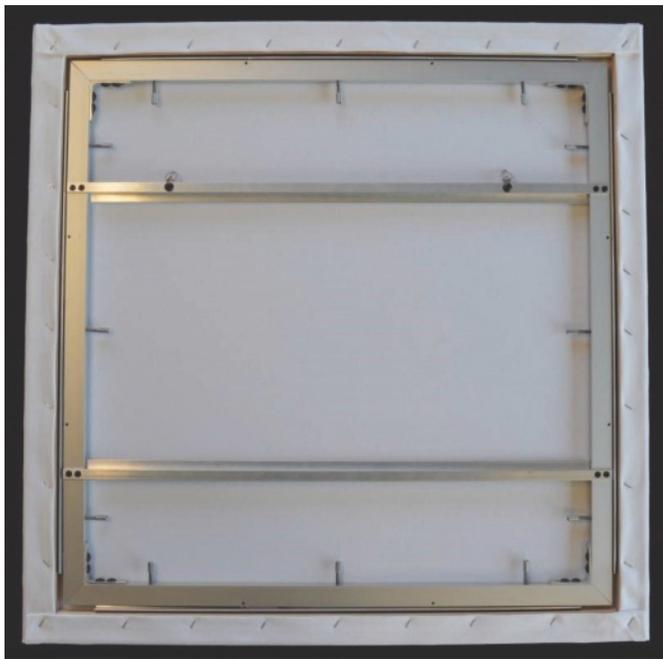


Figure 3. *TWP*² insert placed within a 30 × 30 in. painting (whole verso)

with an outer moveable T-bar that has stainless steel knurled-head thumbscrews located along the stretcher bar, not at the corners. Turning the thumbscrews moves the outer member straight outward. A rigid HDPE polyethylene or black Delrin® resin strip is placed between the U-channel and T-bar as a shim to fill the gap between the metal members and reduce friction. A stainless steel spring pin secures the T-bar in the U-channel (figs. 4, 5).

On the *TWP*² insert, by turning the thumbscrews, the outer T-bar expands the original stretcher by moving the T-bar straight outward. On the *TWP*² artist-grade, the wooden element attached to the outer moveable T-bar (fig. 24) provides a tacking edge for the canvas.

The rigidity of the *TWP*² stretcher is further reinforced by aluminum L-angle plates that secure the aluminum U-channels to the mitered corners with stainless steel screws. The authors recommend that an aluminum Z-bar screwed to the U-channel be incorporated as a crossbar to provide additional rigidity for stretchers more than 30 inches long.

The placement of thumbscrews is critical for ensuring proper movement and optimal surface contact between the T-bar and the original stretcher (*TWP*² insert), and the T-bar/wooden element and the canvas (*TWP*² artist-grade). Thumbscrews should be placed 8–10 inches (20.3–25.4 cm) apart along the stretcher bar, with thumbscrews closest to the edge placed 3–4 inches (7.6–10.2 cm) from the inner corner of the rigid member (e.g., a 30 × 30 in. stretcher should have three thumbscrews per side) (figs. 21, 22). The *TWP*² stretcher mechanism ensures that tensioning is imparted gently and is evenly and independently distributed in each direction.

Hanging devices can be secured either to the inner rigid member (U-channel) or to the crossbar (Z-bar). This arrangement can support the weight of the painting, the original stretcher, and the *TWP*² insert, while maintaining the painting's historical and aesthetic quality.

4. TESTING

4.1 Preparation of Samples

We prepared four 30 × 30 in. and four 12 × 12 in. painting samples for testing. For each sample, the canvas was attached to the stretcher using stainless steel staples. The size and chalk ground were prepared according to traditional recipes (see Recipes). Two brush coats of size were applied to the stretched canvas, followed by two additional brush coats of gesso. Brush marks were smoothed with sandpaper. The final ground was ~180 μm thick.

4.2 Relative-Humidity Chambers

Five relative-humidity chambers were constructed of expanded polyurethane boards faced with aluminum foil. They were assembled into parallelepipeds measuring ~36.5 in. w × 36.5 in. l × 12 in. h (92.7 cm w × 92.7 cm l × 30.5 cm h). Foil-covered sides faced the interior of the chamber so that experimental relative-humidity levels could be maintained once the chamber was sealed. The relative-humidity chambers were stored at a stable temperature of ~20°C.

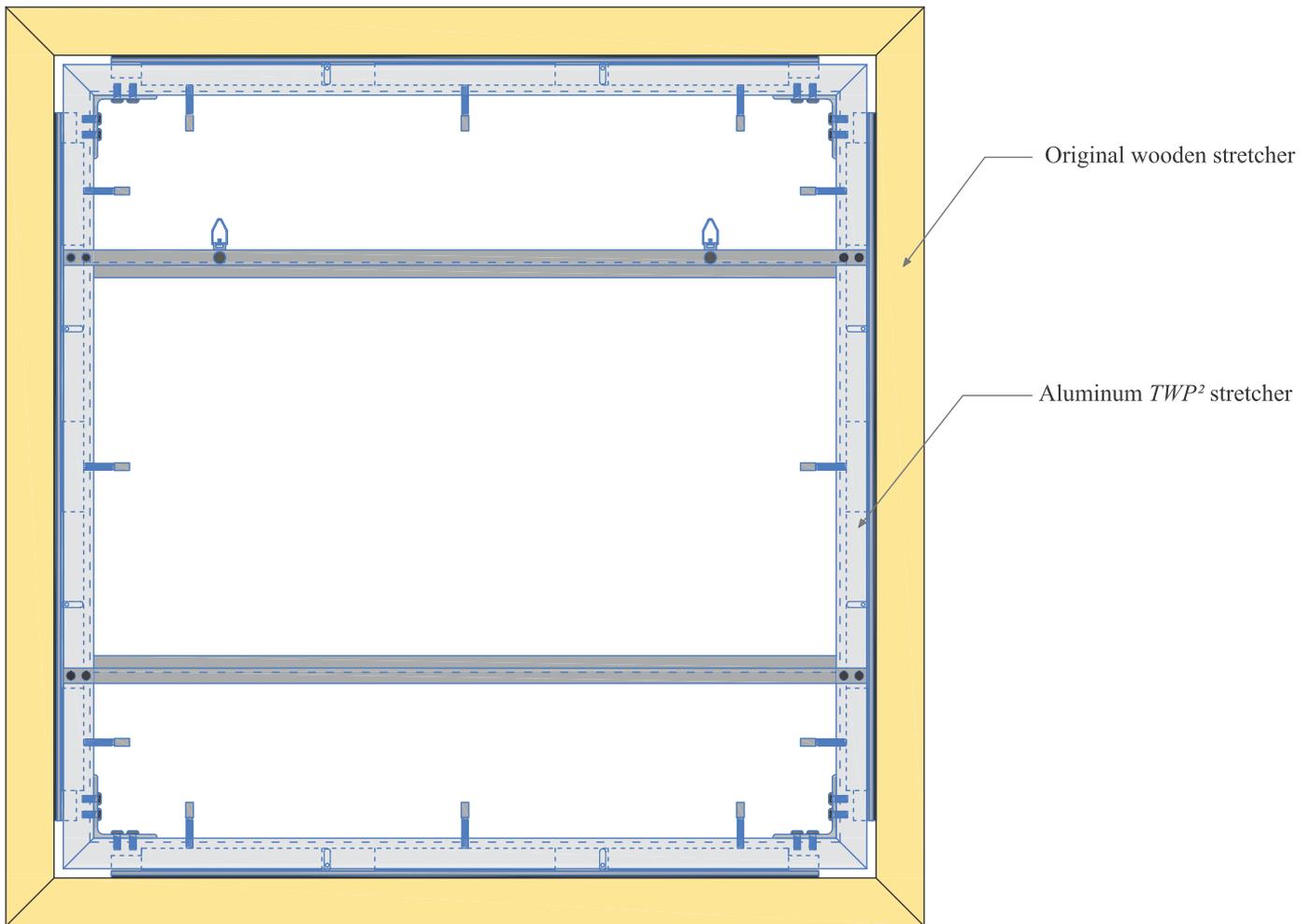


Figure 4. *TWP² insert* placed inside an original stretcher (elevation)

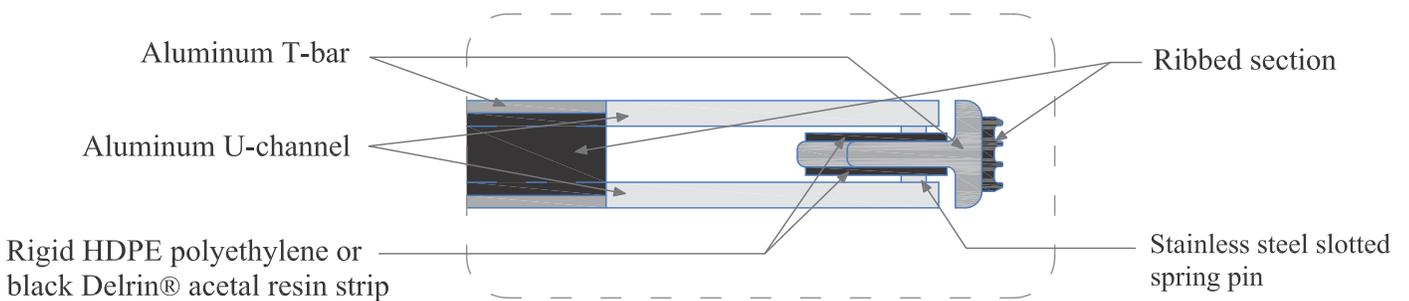


Figure 5. Cross-section of *TWP² insert*

4.3 Testing: Samples, Settings, and Methods

We conducted tests to compare mechanical changes induced by expansion of keyable wooden stretchers, the *TWP² insert*, and the *TWP² artist-grade* (table 1). Test samples 1 and 2 were used as controls (tension was not adjusted). Canvas tension was

adjusted via keying-out (keyable wooden stretchers) and threaded thumbscrews (*TWP² stretchers*). Samples were placed into relative-humidity chambers and subjected to cycles of extreme conditions of relative humidity, fluctuating between 0% (est.) and 100% (est.), for a total of 14 sets over a six-month

Table 1. Testing of painting samples

<i>Test Samples</i>		<i>Experiments</i>
		<i>RH cycling (~0% → ~100% RH)</i>
Test I <i>Keyable</i> wooden stretchers	Test IA Sample 1 – 30 × 30” Sample 2 – 12 × 12”	Control
	Test IB Sample 3 – 30 × 30” Sample 4 – 12 × 12”	Expanding stretcher via keying-out
Test II <i>TWP</i> ² <i>insert</i> stretchers	Sample 5 – 30 × 30” Sample 6 – 12 × 12”	Expanding stretcher bars via threaded thumbscrews
	Test III <i>TWP</i> ² <i>artist-grade</i> stretchers	Sample 7 – 30 × 30” Sample 8 – 12 × 12”

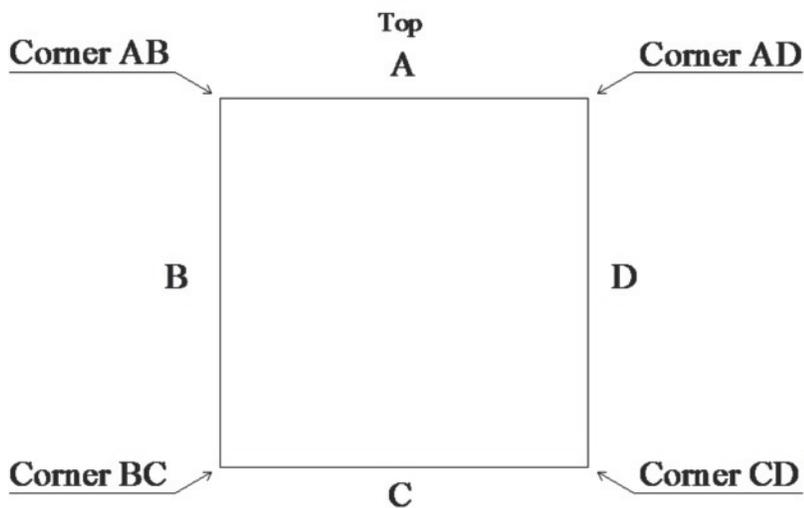
period. The estimated 0% RH level was achieved by placing 0% RH silica gel on a tray at the bottom of the relative-humidity chamber. Moisture in the silica gel was previously evaporated in an oven at 110°C for half a day. The estimated 100% RH level was achieved by placing dampened sheets of blotting paper at the bottom of the chamber.

4.4 Results of Experiments

The objective of the experiments was to assess and compare the mechanical changes induced by expansion with traditional

keyable wooden stretchers and *TWP*² stretchers under conditions of extreme relative-humidity fluctuations. Our assessment focused on the stretchers’ response (dimensional movement or bending) throughout the relative-humidity cycling, as well as craquelure patterns formed on the paintings as a result of expansion and relative-humidity cycling (fig. 6).

Before the relative-humidity cycling experiments began, minor cracks in the 30 × 30 in. samples were observed on the corners and on random areas on the surface of the paintings (see



Painting sample labelling: edges and corners, front view.

Figure 6. Labeled edges and corners of painting samples (front view)

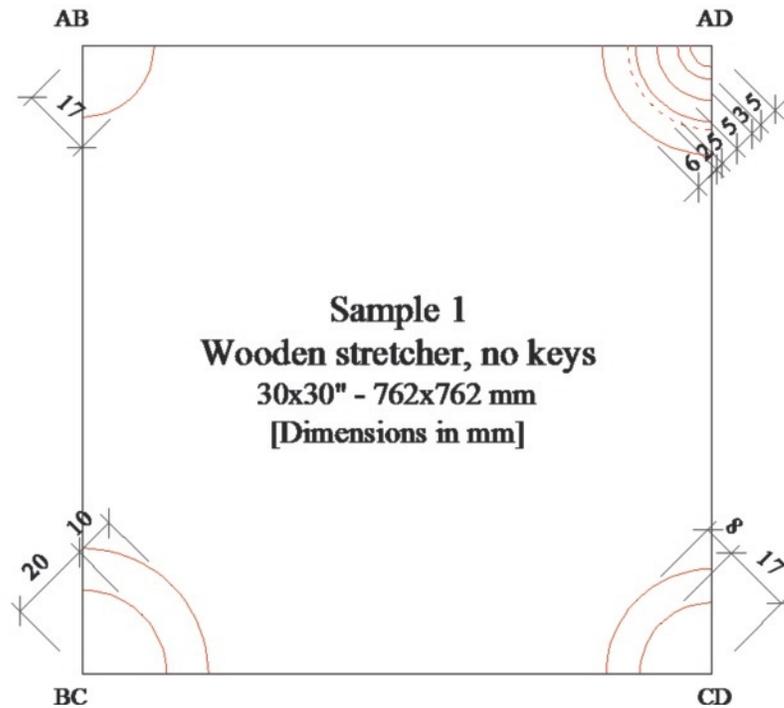


Figure 7. Sample 1, showing distance between cracks that developed after 14 RH sets. The number of cracks at each corner was AB: 1, AD: 5 plus 1 faint crack, CD: 2, and BC: 2

Appendix A). These inherent cracks most likely resulted from canvas preparation and minor defects or creases in the canvas.

Tables 2 and 3 (Appendix A) detail the development of cracks in the painting samples during relative-humidity testing, particularly cracks in the corners of painting samples 1–4 and 5–8 during each set of relative-humidity cycles. In the tables, the terms “cracks” and “faint cracks” represent highly subjective judgments by the testers; however, for our purposes, the term “faint cracks” indicates a lack of both continuous development across the corner and noticeable depth. The wooden stretchers of samples 3 and 4 were keyed-out after each set of lower relative humidity, when the size and gesso layers were more brittle. The *TWP*² stretchers of samples 5–8 were expanded after each relative-humidity set using thumbscrews.

Sample 1 (30 × 30 in. wooden stretcher, no keying-out) developed corner stress cracks from relative-humidity set 4 onwards. After 14 relative-humidity sets, the number of cracks at each corner was AB: 1, AD: 5 (plus an additional faint crack), CD: 2, and BC: 2 (figs. 7, 8). Cracks that developed at corners AB, BC, and CD fell within approximately the same range of distance from the edge of the sample. Cracks that developed at corner AD were more compact, but overall, the crack furthest from the edge fell within a similar range of distance as cracks in the other corners.



Figure 8. Sample 1. After 14 RH sets, corner AD had 5 cracks, 3 of which are fine and thus difficult to capture photographically, and 1 faint crack

Sample 3 (30 × 30 in. wooden stretcher, keyed-out) developed corner cracks earlier than sample 1 (from relative-humidity set 3), but from set 11 onwards no additional cracks developed. After 14 relative-humidity sets, the number of cracks at each

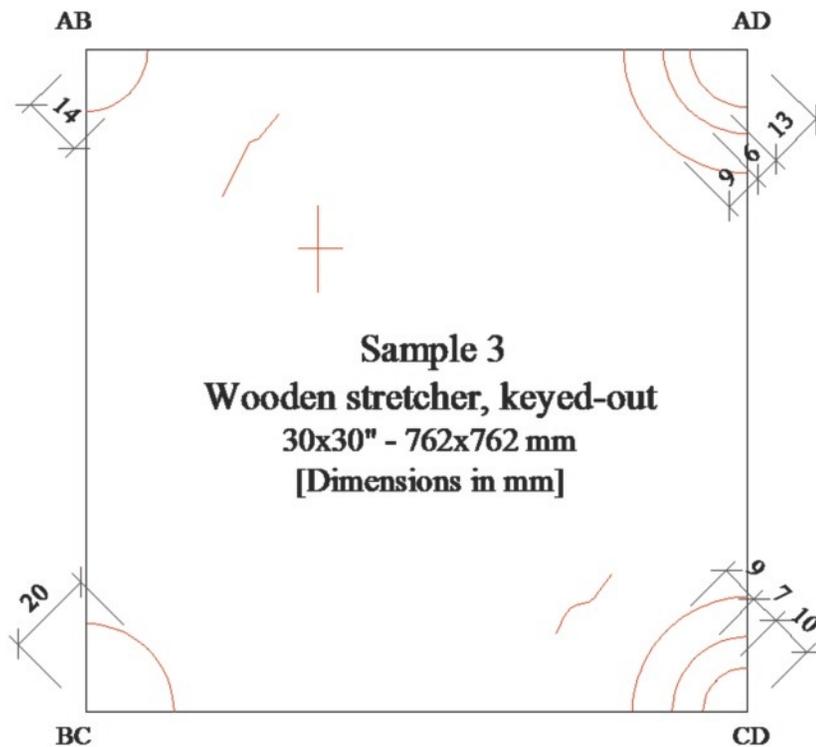


Figure 9. Sample 3, showing cracks that developed after 14 RH sets and the distance between cracks. The number of cracks at each corner was AB: 1, AD: 3, CD: 3, and BC: 1. In addition, there were 2 single and 2 cross-shaped cracks on the surface

corner was AB: 1, AD: 3, CD: 3, and BC: 1 (figs. 9, 10). Corner cracks developed symmetrically along the horizontal axis and fell within approximately the same range of distance from the edge of the sample. Some cracks developed on the surface, but there were no cracks radiating from the corners as a result of keying-out.

Sample 5 (30 × 30 in. *TWP² insert*) developed corner and surface cracks during relative-humidity sets 6–8 and 14. There was no visible symmetry between the corner cracks along the horizontal and vertical axes. Overall, the range of distance from cracks to corner was approximately the same for each corner. After 14 relative-humidity sets, the number of cracks at each corner was AB: 1, AD: 0, CD: 1 faint crack, and BC: 2 (plus an additional faint crack) (figs. 11–13).

Sample 7 (30 × 30 in. *TWP² artist-grade*) developed no corner cracks throughout the relative-humidity cycling experiment. After four relative-humidity sets, a draw developed at corner AD, which was corrected by detaching the canvas at that corner, reattaching the canvas, and tightening the thumbscrews. After eight relative-humidity sets, two single, fine, surface cracks developed on the lower left quadrant (figs. 14, 15).



Figure 10. Sample 3. After 14 RH sets, corner AD had 3 cracks

None of the small painting samples (12 × 12") developed any cracks after being subjected to the same extreme environmental fluctuations (figs. 16, 17).

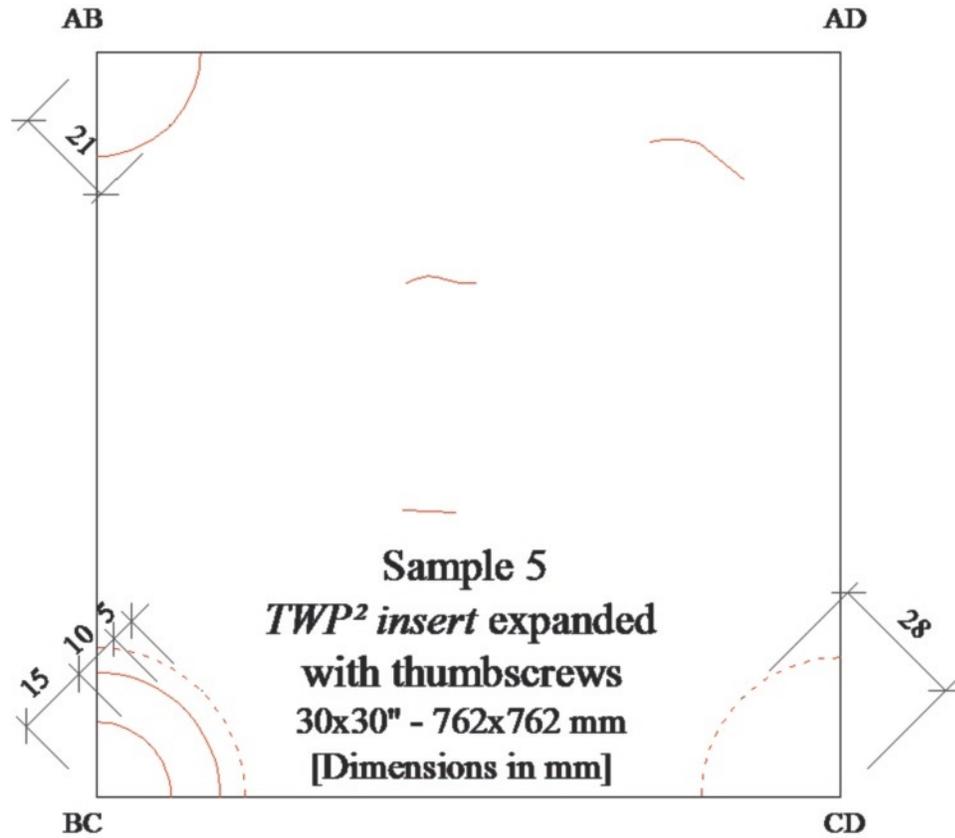


Figure 11. Sample 5, showing cracks that developed after 14 RH sets and the distance between cracks. The number of cracks at each corner was AB: 1, AD: 0, CD: 1 faint crack, and BC: 2 plus 1 faint crack. There were also 3 single surface cracks



Figure 12. Sample 5, corner AD. After 14 RH sets there were no corner cracks, but there was a mechanical surface crack measuring ~10 cm and located ~11 cm from the right edge



Figure 13. Sample 5. After 14 RH sets corner BC had 2 cracks plus 1 faint crack

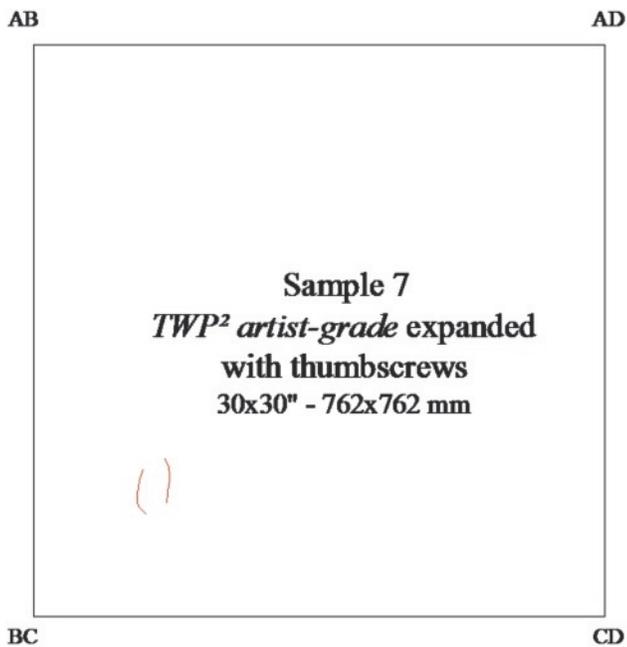


Figure 14. Sample 7. After 14 RH sets there were no cracks visible in the corners and only 2 fine single cracks on the surface



Figure 15. Sample 7, corner AD, after 14 RH sets

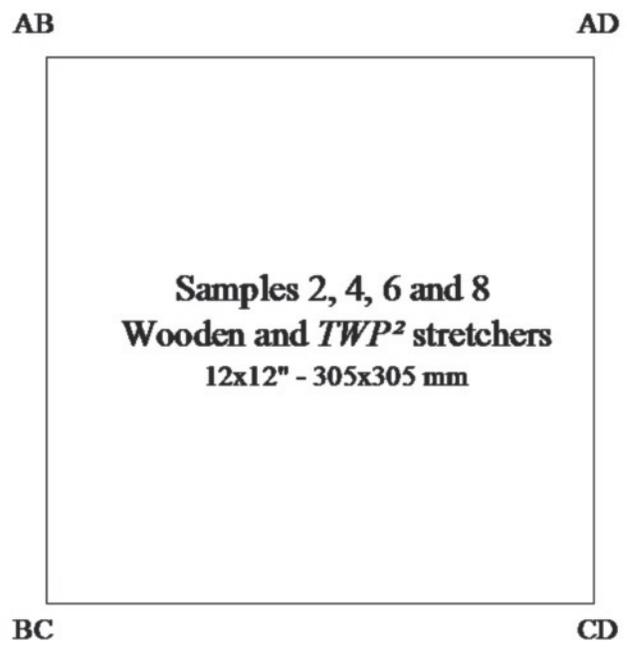


Figure 16. Samples 2, 4, 6, and 8. No cracks developed



Figure 17. Sample 6, whole front. After 14 RH sets, no cracks developed

At the end of the relative-humidity cycling, samples 1 and 3 had a total of 11 and 8 corner cracks, respectively. Sample 1, which was not tensioned during relative-humidity cycling, had slightly more cracks than the keyed-out sample. Sample 5 had a total of five corner cracks. (This sample had cracks before the

experiment began, which may have affected the development of craquelure). Sample 7 had no cracks. Overall, both types of *TWP*² stretcher (samples 5 and 7) developed considerably fewer corner cracks than the traditional wooden stretchers (samples 1 and 3).

5. DISCUSSION

5.1 Craquelure Patterns

Our analysis of craquelure patterns focused on those initiated by mechanical stresses within the composite structure of the painting (e.g., environmental stresses and stresses induced by expansion of the stretcher) and craquelure patterns created by external mechanical pressure or impacts (Keck 1969). Mechanical cracks develop when the canvas is unable to adequately relieve stress (Mecklenburg 1982; Berger and Russell 1994). At low humidity, wavelike cracks radiate from the corners as a result of increased stress within all layers of the composite structure, including stretcher contraction; by keying-out a stretcher, linear cracks (perpendicular to the wavelike) radiate from the corners (Mecklenburg and Tumosa 1991).

The authors compared the craquelure patterns that developed on the painting samples in their experiments with examples previously described (Colville, Kilpatrick, and Mecklenburg 1982; Karpowicz 1990; Mecklenburg and Tumosa 1991; Michalski 1991). The only pattern that developed in their samples (wooden stretchers and *TWP² insert*) was curved, wavelike lines that radiated from the corners. These cracks were generally fine with narrow apertures; some were very faint, especially the ones closest to the edge. In general, each corner developed a different number of cracks. At most, two corners on the same sample developed the same number of cracks. This relates to the fact that being a human factor, the force applied when stretching a canvas is uneven. Some fine surface cracks developed on our samples, possibly resulting from the application of the coating layers and/or minor defects (creases) in the fabric support. Though they are practically invisible when the canvas is under tension, these fine cracks can propagate through the gesso layers. No tacking cracks, middle bisector cracks, or bias cracks developed (Michalski 1991). (None of the paintings became slack enough to make contact with the stretcher bars, ruling out the possibility of stretcher bar edge cracks.)

Sample 3, which was keyed-out, did not develop linear cracks that radiated from the corners, as previously described (Keck 1969; Colville, Kilpatrick, and Mecklenburg 1982; Mecklenburg 1982; Karpowicz 1990; Mecklenburg and Tumosa 1991), even though the keys were driven in at the end of 0% RH cycling, when size and gesso layers are brittle. Possible explanations for the lack of this type of craquelure include: (1) the expansion provided by keying-out was not effective; (2) exposure to too few relative-humidity sets; (3) in the experience of conservators, this type of cracking is uncommon (Karpowicz 2013); and (4) radial corner cracks are subtle (Michalski 1991).

At the end of the relative-humidity cycling experiment, sample 1, the painting that underwent relative-humidity cycling without further tensioning of its wooden stretcher, had slightly more cracks than the keyed-out sample 3, showing that the

extent of deformation is slightly higher. Nonetheless, canvases with both the *TWP² insert* and the *TWP² artist-grade* (samples 5 and 7) developed considerably fewer corner cracks than the canvases with traditional wooden stretchers (samples 1 and 3). This shows that the magnitude of canvas deformation is greater with a traditional wooden stretcher system than with a *TWP²* stretcher. Deformation occurs when the stretcher expands or contracts, or when the canvas cannot be made uniformly taut. Our experiments demonstrated that adjusting the thumbscrews on the new *TWP²* stretcher provides uniform tension over the entire surface of a canvas more effectively than keying-out the corners of a wooden stretcher. Keying-out creates excessive tension primarily at the corners, increasing the number of corner cracks without adequately transmitting tension to the center of the canvas. Thus, the *TWP²* stretcher can prevent corner cracks while providing superior structural support that protects the integrity of the paint surface and the painting as a whole. Our tests also led to improvements in the prototype, such as adjusting the distance between the thumbscrews and their distance from the edge of the rigid aluminum member, which provided better contact throughout the length of the stretcher bar and evenly distributed tension.

None of the 12 × 12 in. painting samples (without or with keys, *TWP² insert*, or *TWP² artist-grade*) developed cracks, showing that size affects the development of stress cracks. RH-induced deformations are less pronounced on small-scale paintings; however, it is possible that craquelure would eventually develop over time.

Sample 7 (30 × 30 in.) had a corner draw. Corner draws are caused by expansion of the fabric and in response to environmental fluctuations. They may also be caused by forces exerted on the bias of the fabric, which creates greater stretch (Young and Jardine 2012). The *TWP²* stretchers used in our tests had only two thumbscrews per bar. Our experiments revealed the need to add one additional thumbscrew per bar to provide better contact throughout the length of the stretcher and possibly prevent corner draws.

Time and budget constraints dictated that samples be examined visually and measured with simple equipment. Further testing is needed to provide more objective data that will clarify comparisons of the traditional wooden stretcher and the *TWP²* aluminum stretcher. Testing could be improved by extending the relative-humidity cycling to assess the long-term effects of extreme relative-humidity fluctuations; evaluating the extent of craquelure patterns and deformation of the canvas; and experimenting with temperature variables. The use of optical systems such as electronic speckle pattern interferometry or digital image correlation could provide systematic and thorough assessments of strain fields (which would allow the calculation of the stress fields) (Dulieu-Barton et al. 2005; Young 2012).

5.2 Expansion of Stretcher Bars: Traditional Wooden Stretcher versus *TWP*² Aluminum Stretcher

Successive cycles of temperature and relative-humidity fluctuations can undermine a canvas's original tension and cause it to slacken. This is the most common reason for periodic keying-out (Berger and Russell 1994). However, keying-out expands a conventional stretcher only at the corners, not along the edges, which causes further variations in the overall tension of a painting (Berger 1984). Repeated or excessive keying-out of the stretcher does not resolve the problem of overall slackening, particularly with large-scale paintings (Chiantore and Rava 2013). It does, however, concentrate stress at the corners, which can ultimately fracture the canvas in those areas. The tension focused at the corners of the canvas, along with the tension exerted by the canvas along the stretcher bar, prevent the bar from moving freely and may cause it to bend. High tension in the corners will not be evenly distributed across the surface of the painting. This ineffective tensioning will be especially noticeable in the center of the canvas. Expanding on work by Mecklenburg (2012), the authors analyzed strains on the corners and center of a canvas induced by keying-out of a wooden stretcher (fig. 18). The stretcher measured 760 × 635 mm, with bars 75 mm wide. For our investigations, the authors assumed a deformation (δ) of 1.5 mm vertically and horizontally on each corner, and defined strain (ϵ) as deformation (δ) in relation to the original length of the bars.

In the figure above, solid lines indicate the stretcher bars before expansion, and dotted lines indicate deformation after expansion. Assuming the stretcher bars bend, vertical strain will diminish from 0.00395 to 0.00263 or 0.00197, depending on whether displacement at the center of the bar (x) is $2/3$ (0.00263) or $1/2$ (0.00197) of total displacement ($1.5 \times 2 = 3$ mm). (Values of magnitude of bending should be taken as estimations.) Center strain is directly proportional to the amount of bending in the stretcher bar; that is, if the bar deflects half of the corner displacement ($x = 1/2 \delta$), the center strain will be half what it would be if there were no bending. To overcome this ineffective tensioning in the center, the tendency is to increase expansion at the corners, but this just creates even higher strains, and thus stresses. Assuming the bar deflects half of the displacement, to achieve higher strain in the center, expansion at the corners would need to double; i.e., strain at the corners would need to go from 0.0196 to 0.0393. Focusing expansion at the corners inevitably shifts the canvas in the bias direction, where tensile strength is lowest, and thus stretch is greater and tensioning is least effective (Young and Jardine 2012). Bending of the stretcher bars, and consequent lack of tension in the center of the canvas, is even more problematic in oversize paintings.

Next, the authors inserted a *TWP*² insert stretcher into an original wooden stretcher with the same dimensions as the stretcher in the

previous experiment. Then they expanded the stretcher bars in each direction by turning the thumbscrews (fig. 19).

In the previous figure, solid lines indicate the original and *TWP*² insert stretcher bars before expansion. Dotted lines indicate their position after expansion. Thumbscrews are positioned along the stretcher bar, including in the center, allowing uniform movement of the outer aluminum T-bar, which imparts evenly distributed tension. Turning the thumbscrews expands the aluminum T-bar in a straight line in conjunction with the original wooden stretcher bar, eliminating any bending of the bars. Assuming a 1.5-mm δ in both directions, the vertical and horizontal strains in the center will be 0.00395 and 0.00472, respectively. Because there is no bending of the stretcher bar, the strain field will be evenly distributed throughout the painting's surface, except at the corners, where strain distribution is heterogeneous (Young and Hibberd 1999). Strain at the corners (same location as on the previous example) will be 0.0196. According to our two theoretical models, compared to the keyed-out wooden stretcher, the *TWP*² insert achieved the same magnitude of strain in the center of the canvas, while creating less strain at the corners. Thus, the self-adjusting *TWP*² offers a more effective way of distributing tension over the entire surface of a canvas, making the *TWP*² the best option for oversize paintings where tensioning is more problematic at the center. Furthermore, the *TWP*² can effectively maintain that tension over a long period of time.

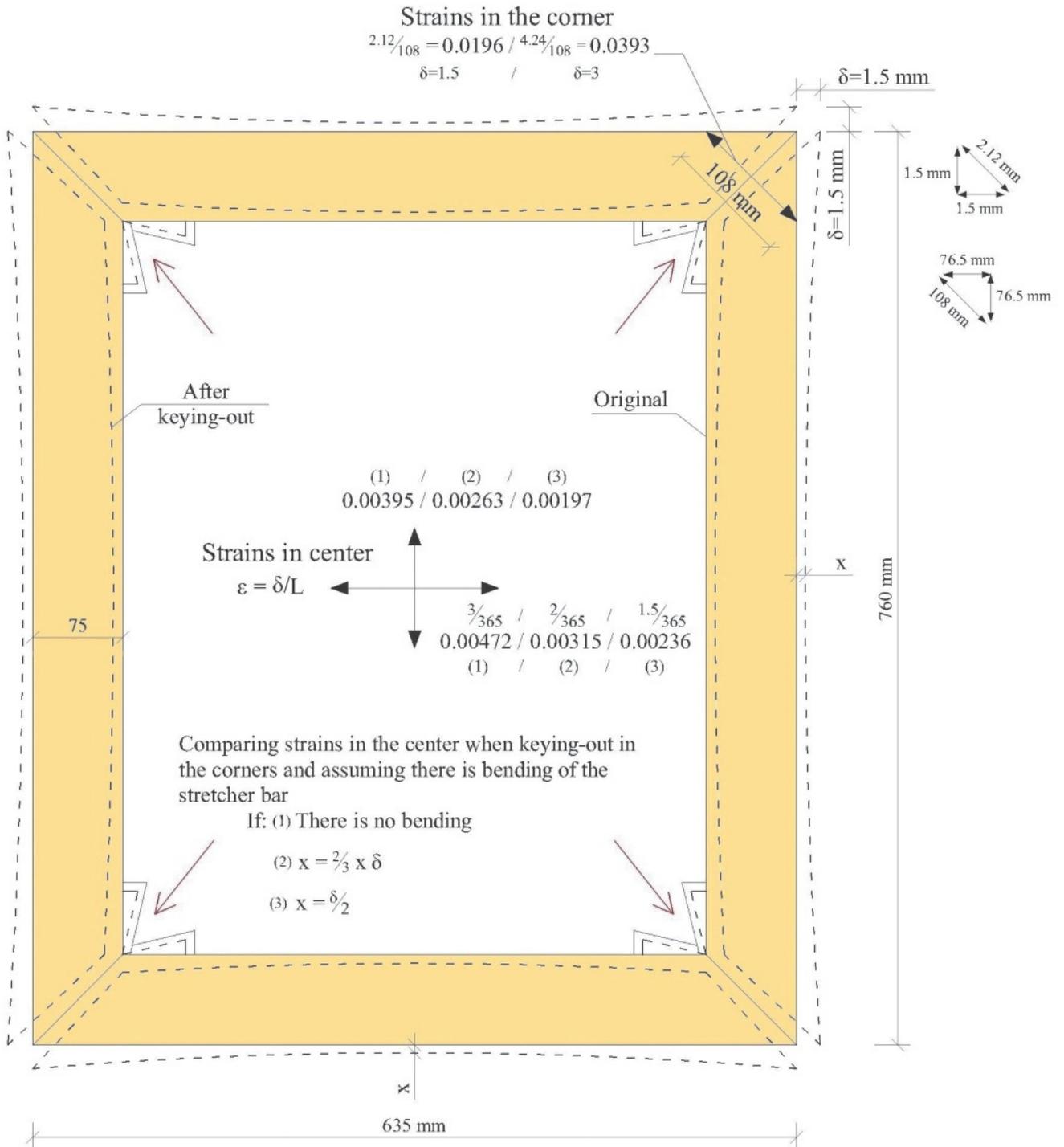
5.3 Response to Changes in Relative Humidity and Temperature

After analyzing the comparative strains incurred on a canvas painting by the expansion of wooden and aluminum stretchers, the authors compared how paintings with wooden stretchers and aluminum stretchers respond to changes in relative humidity and temperature.

5.3.1 Composite Layers of a Painting

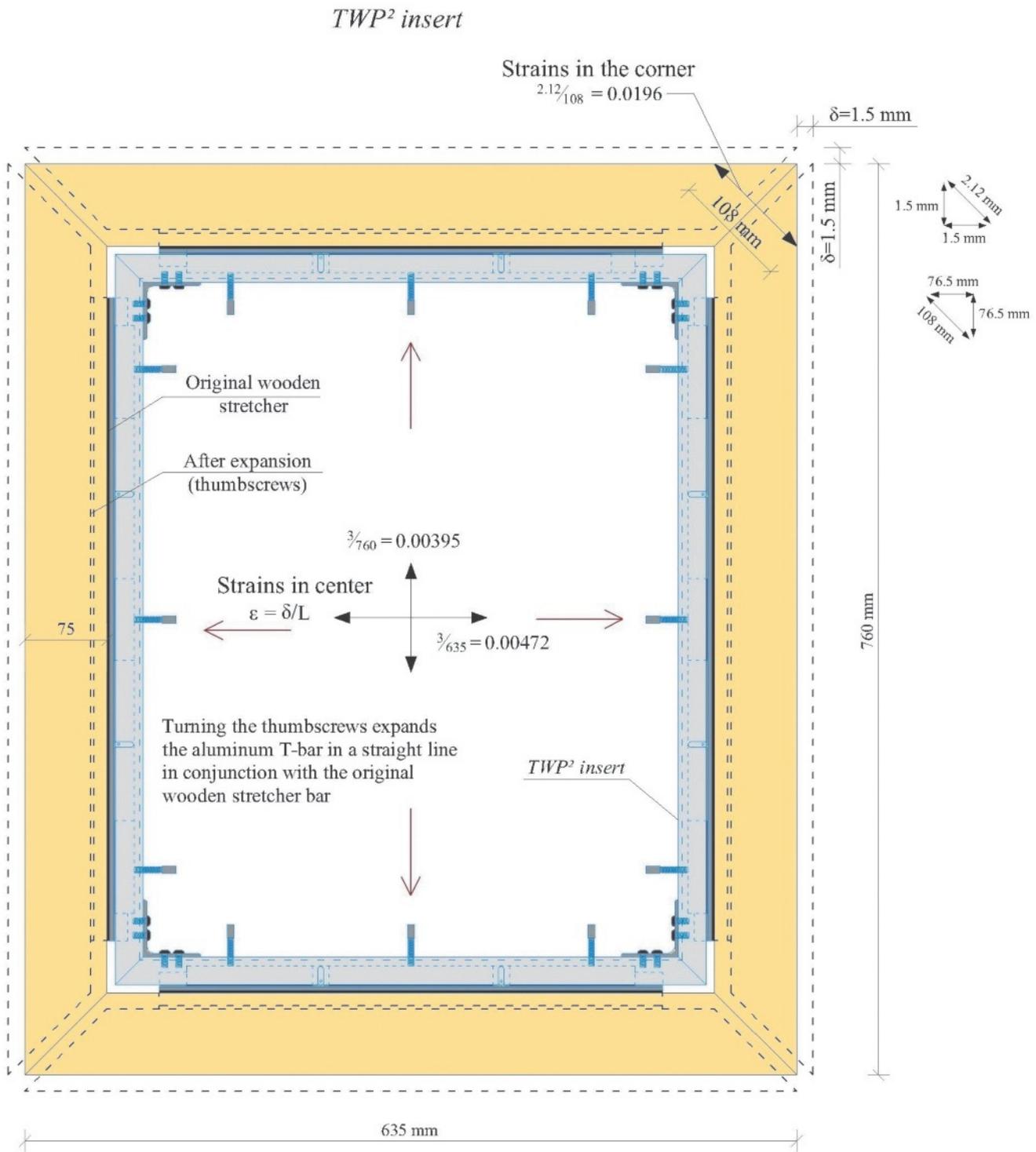
Paintings on canvas lose tension with moisture absorption until relative humidity reaches approximately 80–85%, at which point the tension begins to increase. This inflexion is related to the canvas's tendency to shrink (Hedley 1988). If a painting is attached to a stretcher, stresses on all of its composite layers increase in response to a decrease in either temperature or relative humidity. Of all painting materials, glue is most sensitive to relative humidity (Mecklenburg and Tumosa 1991). Glue responds quickly to environmental changes; hence, in a sized painting, glue is responsible for the majority of damage due to changes in relative humidity. Size and glue respond to fluctuations in relative humidity within minutes to hours. By comparison, it takes days to weeks for stretcher bars to respond to the same fluctuations (Michalski 1991). Therefore, in their tests, the authors decided to run each relative-humidity set for 1–3 weeks. In addition, size and glue ground show greater increases

Traditional keyable wooden stretcher



Theoretical model of strains in the center and corners of a canvas caused by keying-out of a traditional keyable wooden stretcher.

Figure 18. Theoretical model of strains in the center and corners of a canvas caused by keying-out of a traditional keyable wooden stretcher



Theoretical model of strain in the center and corners of a canvas after expanding the stretcher bars of an aluminum *TWP2 insert* via thumbscrews.

Figure 19. Theoretical model of strain in the center and corners of a canvas after expanding the stretcher bars of an aluminum *TWP² insert* via thumbscrews

in tension in response to low levels of relative humidity than to low temperatures. Thus, to minimize variables, temperature variations were not considered in our tests (Michalski 1991).

5.3.2 Wooden Stretchers versus Aluminum Stretchers

The expansion or shrinkage of a stretcher will be reflected in strains in the painting it supports. The dimensional response of wood to moisture and temperature is different depending on the direction in which wood is cut (tangential, radial, or longitudinal). The authors calculated moisture coefficients of expansion (γ) for different species of wood assuming a tangential cut (table 4, Appendix B). If it was a radial cut, the dimensional change would be approximately half, and therefore the moisture coefficient of expansion would be roughly half (Mecklenburg 2012). On the other hand, aluminum does not respond to relative-humidity changes.

The thermal expansion coefficient (α) for aluminum is 24×10^{-6} per $^{\circ}\text{C}$ (Nave 2013). The coefficients of thermal expansion for different species of wood are outlined in table 5 (Appendix B). Wood's radial response to changes in temperature is generally higher than aluminum. A comparison of the values listed in tables 4 and 5 reveals that the moisture coefficients (γ) of wood are much greater than the thermal coefficients (e.g., for cottonwood, $\gamma = 0.042$ and $\alpha = 0.000023$), meaning that wood is more sensitive to changes in relative humidity than to changes in temperature. Fluctuations in relative humidity lead to greater expansion and contraction of a wooden stretcher, which ultimately leads to higher stresses and strains in the canvas painting.

An aluminum stretcher can greatly reduce the strains imposed on a painting by environmental fluctuations. Since there is a wood component to both the *TWP² insert* and *TWP² artist-grade*, strains due to environmental fluctuations cannot be entirely avoided; however, the width of the wood member in the *TWP² artist-grade* can be varied as needed, since structural support is provided by the aluminum members. Another advantage of an aluminum stretcher is that it does not warp in response to changes in relative humidity, as wooden stretchers do.

6. APPLICATIONS

The *TWP² insert* is designed to fit inside an existing or original stretcher. It can strengthen a weak original stretcher and provide dimensional stability. Tension can be adjusted by turning thumbscrews that exert gentle, even pressure across the entire surface of the painting. The *TWP² insert* also provides effective tension adjustment at the center of a painting, where traditional expansion via keying-out of the corners is least effective. The *TWP²* is well suited for large-format, traditional,

or contemporary paintings. In addition, the magnitude of deformation on a canvas supported by a *TWP²* stretcher is less than that seen with a traditional wooden stretcher. The *TWP²* can be fitted and dismantled simply by loosening the thumbscrews.

When the authors fitted a 150-year-old painting with the newly designed *TWP² insert* as an auxiliary support inside the original stretcher, planar distortion in the canvas was immediately corrected (fig. 20). No heat, moisture, or weight was necessary to correct this planar distortion, thus preserving the character and integrity of the painting. They are currently investigating the use of a *TWP² artist-grade* in a contemporary painting with heavy impasto, which makes tension adjustment even more critical.

7. CONCLUSIONS

Extreme fluctuations in relative humidity can cause rapid and significant changes in tension that produce craquelure on the surface of a painting. The results of this study demonstrated and confirmed this phenomenon. The theoretical models of strain in both the *TWP²* stretcher and a traditional keyable wooden stretcher increased our understanding of the problems arising from bending in a wooden stretcher caused by expansion. The major advantages of the *TWP²* stretcher are its capacity for independent directional expansion and its construction of stable aluminum that does not react to relative-humidity fluctuation. Our tests demonstrated that the *TWP²* stretcher helps to prevent corner cracking, which can ultimately propagate further deterioration. The self-adjusting *TWP²* stretcher offers a more effective way of tensioning the canvas and maintaining tension for a longer term. Our innovative stretcher design could not only transform strategies for preserving at-risk and large-format

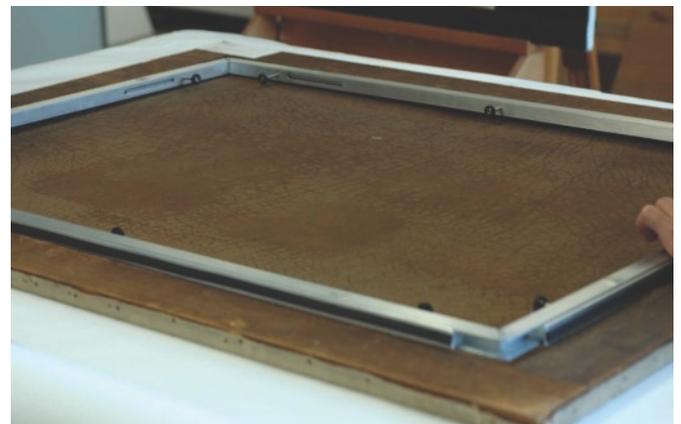


Figure 20. A *TWP²* insert is placed inside the original wooden stretcher of a 150-year-old painting

paintings, but could also influence the design and fabrication of large-scale canvases. Further research with a greater number of samples and more precise measuring instruments will improve our understanding of the mechanical stress and strain resulting from stretcher expansion.

APPENDIX A

Before the relative-humidity cycling, samples 1 and 3 had a maximum of 1 or 2 minor cracks in one corner. Samples 2 and 4 (12 × 12") had no cracks.

Table 1. Experimental Development of Corner and Surface Cracks on Painting Samples 1–4 (Wooden Stretchers)

Samples Sets	1 Wooden Stretcher, 30 × 30", No Keys	2 Wooden Stretcher, 12 × 12", No Keys	3 Wooden Stretcher, 30 × 30", Keyed-Out	4 Wooden Stretcher, 12 × 12", Keyed-Out
1: 0% RH	Minor cracks	No cracks	Minor cracks	No cracks
2: 100% RH	No change	No change	No change	No change
3: 0% RH	No change	No change	AB: 1 crack AD: 2 cracks CD: 1 crack BC: 1 crack	No change
4: 100% RH	AB: 1 crack AD: 4 cracks CD: 1 crack (+ 1 faint crack) BC: 2 cracks	No change	AB: 1 crack AD: 2 cracks CD: 2 cracks BC: 1 crack	No change
5: 0% RH	No change	No change	No change	No change
6: 100% RH	No change	No change	No change	No change
7: 0% RH	No change	No change	AB: 1 crack AD: 2 cracks (+ 1 faint crack) CD: 3 cracks BC: 1 crack	No change
8: 100% RH	No change	No change	No change	No change
9: 0% RH	No change	No change	No change	No change
10: 100% RH	AB: 1 crack AD: 4 cracks CD: 2 cracks BC: 2 cracks	No change	AB: 1 crack AD: 3 cracks CD: 3 cracks BC: 1 crack	No change
11: 0% RH	No change	No change	No change (cracks on corners) Cracks on surface	No change
12: 100% RH	No change	No change	No change	No change
13: 0% RH	AB: 1 crack AD: 5 cracks CD: 2 cracks BC: 2 cracks	No change	No change	No change
14: 100% RH	AB: 1 crack AD: 5 cracks (+ 1 faint crack) CD: 2 cracks BC: 2 cracks	No change	No change	No change

Before relative-humidity cycling, samples 6 and 8 (12 × 12 in.) and 7 (30 × 30 in.) had no cracks. Sample 5 had a slightly noticeable crack on corner BC. Three mechanical surface cracks may have been related to indentations on

the back of the canvas (possible fabric defect), to ground application, or to the fact that the TWP2 insert was fitted approximately one month after the canvas was prepared.

Table 2. Experimental Development of Corner and Surface Cracks on Samples 5–8 (*TWP² insert* and *artist-grade*).

Samples Sets	5 <i>TWP² insert,</i> 30 × 30", Expanded Via Thumbscrews	6 <i>TWP² insert,</i> 12 × 12", Expanded Via Thumbscrews	7 <i>TWP² artist-grade,</i> 30 × 30", Expanded Via Thumbscrews	8 <i>TWP² artist-grade,</i> 12 × 12", Expanded Via Thumbscrews
1: 0% RH	BC: faint crack	No cracks	No cracks	No cracks
2: 100% RH	BC: 1 crack	No change	No change	No change
3: 0% RH	No change	No change	No change	No change
4: 100% RH	No change	No change	No change	No change
5: 0% RH	No change	No change	No change	No change
6: 100% RH	AB: faint crack BC: 1 crack	No change	No change	No change
7: 0% RH	AB: faint crack BC: 1 crack CD: faint crack	No change	No change	No change
8: 100% RH	AB: 1 crack BC: 2 cracks CD: faint crack Surface crack	No change	No change Fine surface cracks	No change
9: 0% RH	No change (cracks on corners) Surface cracks	No change	No change	No change
10: 100% RH	No change	No change	No change	No change
11: 0% RH	No change (cracks on corners) Surface cracks: one crack expanded	No change	No change	No change
12: 100% RH	No change	No change	No change	No change
13: 0% RH	No change	No change	No change	No change
14: 100% RH	BC: 2 cracks (+ 1 faint crack)	No change	No change	No change

APPENDIX B

Table 3. Moisture Coefficients of Expansion (γ) for Different Types of Wood (Tangential Cut Assumed) at Relative-Humidity Intervals of 20%–50% and 50%–80^a

Type of Wood	Moisture Coefficient of Expansion (γ) 20% → 50% RH	Moisture Coefficient of Expansion (γ) 50% → 80% RH
Cottonwood (European poplar)	0.042	0.067
White oak	0.038	0.046
Red oak	0.039	0.059
17 th -century Scots pine	0.043	0.077
Maple	0.046	0.085
Ash	0.044	0.078
Aircraft spruce	0.024	0.026
Sugar pine	0.019	0.019
Spruce	0.025	0.025

^aThe moisture coefficients of expansion are approximate values calculated using the graphs, “Free Swelling Strains vs. Relative Humidity,” provided in (Mecklenburg 2012)

Table 4. Thermal Expansion Coefficients (α) for Different Types of Wood (Weatherwax and Stamm 1956; Wood Science and Technology archive)

Wood	Thermal Expansion Coefficient per °C [50°C–0°C], $\alpha_{\text{radial}} \times 10^{-6}$	Thermal Expansion Coefficient per °C [50°C–0°C], $\alpha_{\text{parallel}} \times 10^{-6}$
Yellow poplar	27.2	3.55
Cottonwood	23.3	3.17
Douglas fir	27.1	3.52
Oak	54	5
Pine	34	5

APPENDIX C

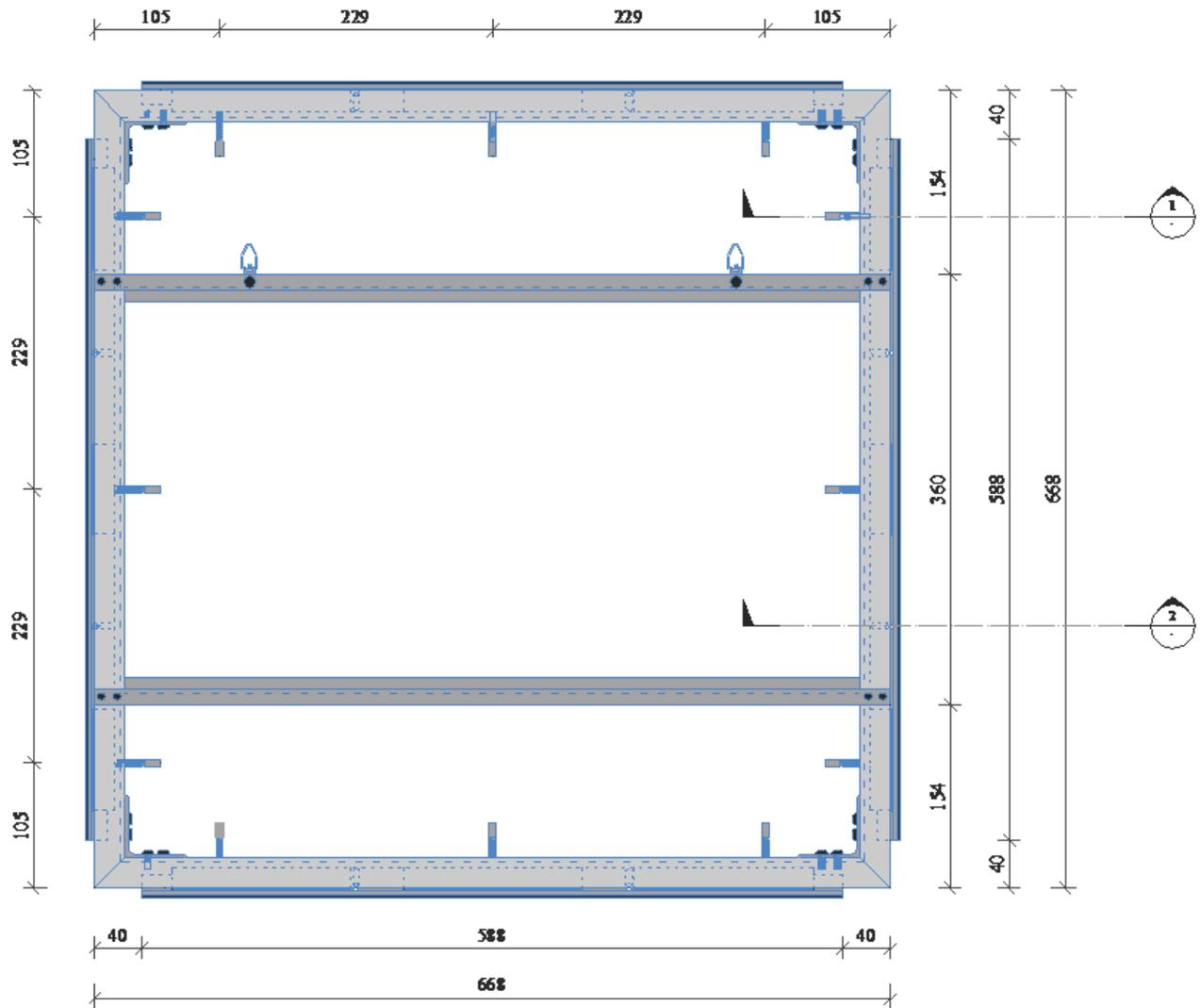


Figure 1. *TWP² insert*, elevation. Dimensions are in millimeters, based on a recent prototype inserted into a 30 × 30 in. (762 × 762 mm) painting sample

Stainless steel knurled-head thumbscrew, slotted

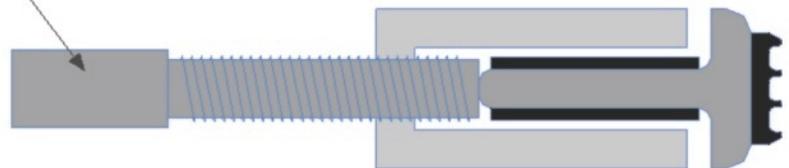


Figure 2. *TWP² insert*, section 1 (see fig. 21)

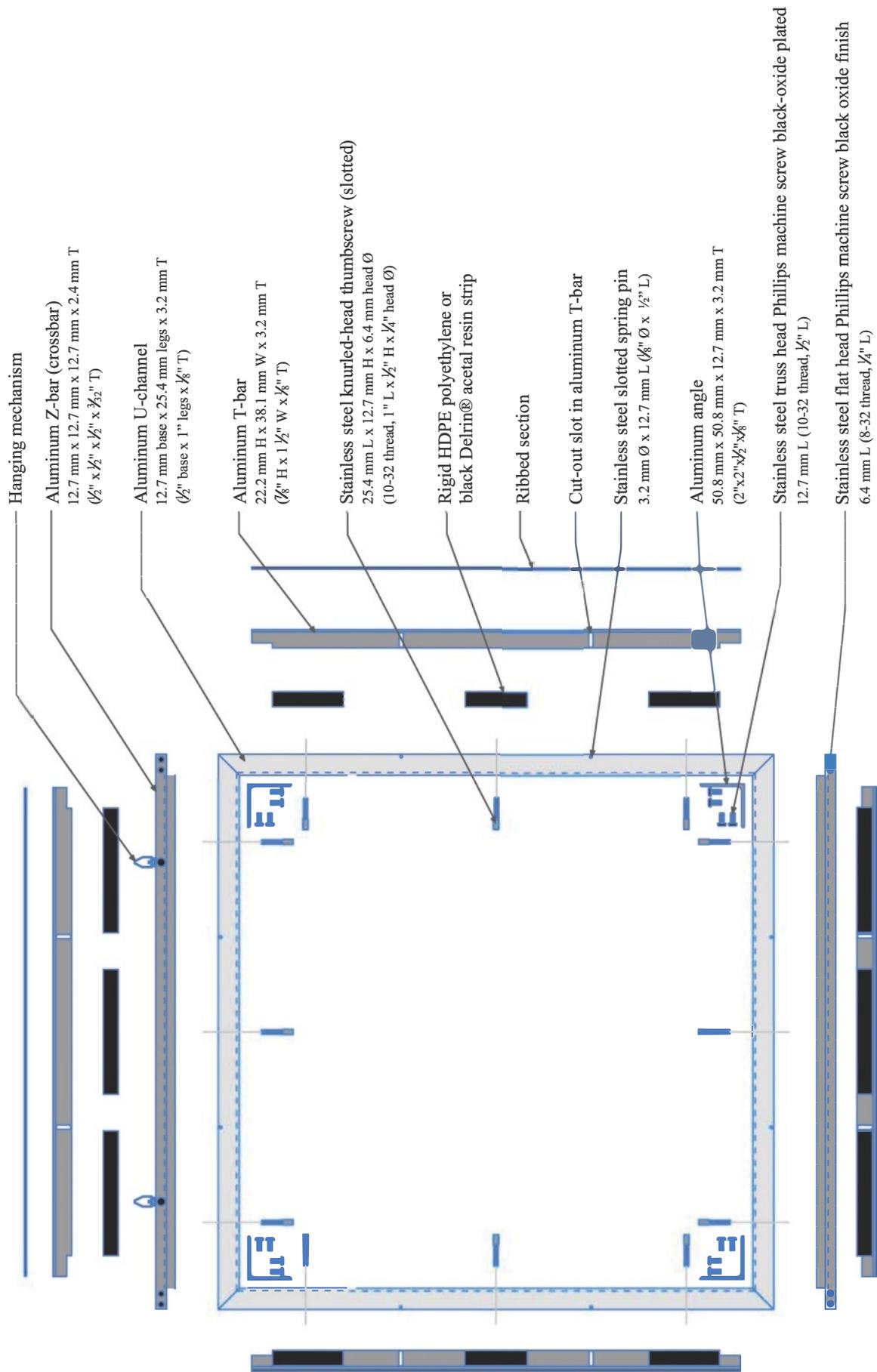


Figure 3. *TWP² insert*, elevation, exploded, based on a recent prototype inserted into a 30 × 30 in. (762 × 762 mm) painting sample

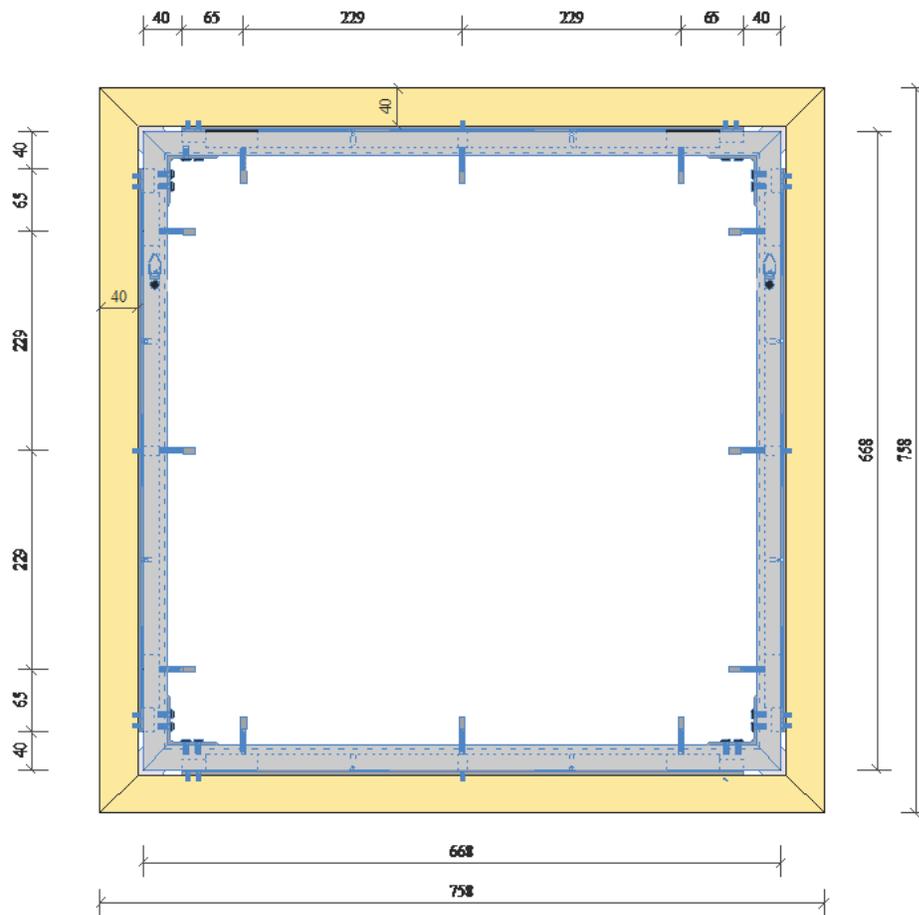


Figure 4. *TWP*² artist-grade, elevation. Dimensions are in mm, based on a 30 × 30 in. (762 × 762 mm) painting sample

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REFERENCES

- AIC, Paintings Group. 2013. Stretchers and strainers. *Painting conservation catalog wiki*. Accessed January 11, 2016. <http://www.conservation-wiki.com/wiki/Paintings>.
- AIC, Paintings Group. Factors to consider. *Painting conservation catalog wiki*. Accessed January 11, 2016. http://www.conservation-wiki.com/wiki/PSG_Stretchers_and_Strainers_-_II._Factors_to_Consider.
- Alustrech. 2013. Accessed January 11, 2016. <http://www.alustrech.com/en/home/>.
- Berger, Gustav A. 1984. A structural solution for the preservation of canvas paintings. *Studies in Conservation* 29(3): 139–142.
- Berger, Gustav A., and William H. Russell. 1994. Interaction between canvas and paint film in response to environmental changes. *Studies in Conservation* 39(2): 73–86.
- Buckley, Barbara A. 2012. Stretchers, tensioning, and attachments. In *Conservation of easel paintings*, eds. J. H. Stoner and R. Rushfield. Oxon and New York: Routledge.
- Canadian Conservation Institute. 1993. CCI Notes 10/9: Keying out of paintings. Accessed January 11, 2016. <http://www.cci-icc.gc.ca/publications/notes/10-9-eng.aspx>.
- Chiantore, Oscar, and Antonio Rava. 2013. 1–8 paintings on canvas. In *Conserving contemporary art: issue, methods, materials, and research*. Los Angeles, CA: The Getty Conservation Institute.
- Ciatti, Marco. December, 2000. The restoration of Caravaggio's *The Beheading of Saint John the Baptist*. Paper presented at Big Pictures, Problems and Solutions for Treating Outsize Paintings, 2005, at Tate Modern, London, organized by the Paintings Section of the Institute of Conservation.

- Colville, James, William Kilpatrick, and Marion Mecklenburg. 1982. A finite element analysis of multi-layered orthotropic membranes with application to oil paintings on fabric. Paper presented at Science and technology in the service of conservation, at Washington DC.
- Dulieu-Barton, Janice M., Leonidas Dokos, Dinah Eastop, Frances Lennard, Alan R. Chambers, and Melin Sahin. 2005. Deformation and strain measurement techniques for the inspection of damage in works of art. *Reviews in Conservation* (6): 63–73.
- Hedley, G. 1988. Relative humidity and the stress/strain response of canvas paintings: uniaxial measurements of naturally aged samples. *Studies in Conservation* 33 (3): 133–148.
- Idelson, Antonio Iaccarino. 2009. About the choice of tension for canvas paintings. *Les dilemmes de la restauration*. Accessed January 11, 2016. <http://ceroart.revues.org/1269>.
- Jackson's Art Supplies. n.d. NB frame aluminium stretcher bars. [cited March 2013]. Accessed January 11, 2016. http://www.jacksonsart.com/Art_Departments-A-Z_All_Departments-Artist_Canvas-Stretcher_Bars-NB_Frame_Aluminium_Stretcher_Bars/c2129_2128_1243_1348_11682/index.html.
- Karpowicz, Adam. 1990. A study in the development of cracks on paintings. *Journal of the American Institute for Conservation* 29 (2): 169–180.
- Katlan, Alexander W. 1992. A guide to stretchers, panels, millboards, and stencil marks. In *Artists' materials*, vol.2, ed. P. H. Falk. Madison, CT: SoundView Press.
- Keck, Sheldon. 1969. Mechanical alteration of the paint film. *Studies in Conservation* 14 (1): 9–30.
- Massey, Robert. 1967. *Formulas for painters*. New York, NY: Watson-Guption Publications.
- Mecklenburg, Marion F. 1982. Some aspects of the mechanical behavior of fabric supported paintings. Washington, D.C.: Smithsonian Institution.
- Mecklenburg, Marion F. 2012a. Session 2: Basic concepts. In *The Structure of Paintings and the Mechanical Properties of Cultural Materials*. Unpublished.
- Mecklenburg, Marion F. 2012b. Session 4: Paintings as structures and failure mechanisms. In *The Structure of Paintings and the Mechanical Properties of Cultural Materials*. Unpublished.
- Mecklenburg, Marion F., and Charles S. Tumosa. 1991. Mechanical behaviour of paintings subjected to changes in temperature and relative humidity. Paper presented at *Art in Transit: Studies in the Transport of Paintings*. Conference on the Packing and Transportation of Paintings at London.
- Michalski, Stefan. 1991. Paintings: their response to temperature, relative humidity, shock, and vibration. Paper presented at *Art in Transit: Studies in the Transport of Paintings*. Conference on the Packing and Transportation of Paintings at London.
- Nave, C.R. 2013. *Thermal expansion coefficients at 20°C*. Department of Physics and Astronomy, Georgia State University, 2013 [cited January 2013]. Accessed January 11, 2016. <http://hyperphysics.phy-astr.gsu.edu/hbase/tables/thexp.html#c1>.
- Buckley, B.A. 2008. Stretchers and strainers. *Painting conservation catalog, Vol.2, Stretchers and strainers*. Washington DC: AIC.
- Adam Karpowicz. 2013. Personal communication
- Philips, Stan. 1992. A new expansion stretcher design. Paper read at Twentieth Annual Meeting of the American Institute for Conservation of Historic and Artistic Works, at Buffalo, New York.
- Rex Art. n.d. Accessed January 11, 2016. <http://www.rexart.com/best-gallery-wrap-stretcher-bars.html>.
- Simon Liu Inc. 2013. [cited March 2013]. Accessed January 11, 2016. <http://www.simonliuinc.com/>.
- Weatherwax, Richard C., and Alfred J. Stamm. 1956. *The Coefficients of Thermal Expansion of Wood and Wood Products*. Forest Products Laboratory (U.S.) report no. 1487 in collaboration with University of Wisconsin. Madison, Wis.: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory.
- Wood Science and Technology archive. Thermal properties. Davis College of Agriculture, Natural Resources and Design, Division of Forestry & Natural Resources. Accessed January 11, 2016. http://web.archive.org/web/20090330062350/http://www.forestry.caf.wvu.edu/programs/woodindustries/wdsc340_7.htm.
- Young, Christina R.T. 2012. Young C.R.T., The Use of 3D ESPI for the Structural Analysis of Paintings on Canvas, *LACONA IX Conference*, London, 2013, 108–115. ISBN 978-1-904982-87-6
- Young, Christina R.T., and Roger D. Hibberd. 1999. Biaxial tensile testing of paintings on Canvas. *Studies in Conservation* 44 (2): 129–141.
- Young, Christina R.T., and Suzanne Jardine. 2012. Fabrics for the twenty-first century: As artist canvas and for the structural reinforcement of easel paintings on canvas. *Studies in Conservation* 57 (4): 237–253.

SOURCES OF MATERIALS

TWP² insert and TWP² artist-grade

Anodized architectural aluminum (alloy 6063) U-channel:
 ½ in. base, 1 in. legs, 1/8 in. thick (T), 6' L (McMaster-Carr 4592T12)

Multipurpose aluminum (alloy 6061) T-bar: 0.125 in. T, 7/8 in. H, 1-1/2 in. W, 8 ft. L (legs machined down to ½ in. W) (McMaster-Carr 1668T14)

Black Delrin® acetal resin strip: 0.031 in. T, 1 in. W (reduced to ¾ in. W) (McMaster-Carr 638T21)

Rigid HDPE polyethylene: 0.040 in. T, 1 in. W, 10 ft. L (McMaster-Carr 8619K714)

18-8 stainless steel slotted spring pins (100 count packs): 1/8 in. diameter, ½ in. L (McMaster-Carr 92373A177)

Knurled-head thumbscrews with shoulder brass: 10-32 thread, ¾ in. L (McMaster-Carr 92421A645)

Clean Seal® ribbed section

Ultra-high molecular-weight (UHMW) polyethylene tenon (*TWP² artist-grade*)

Poplar, fir or basswood strips

Aluminum Z-bar (crossbar): ½ in. × ½ in. × ½ in. × 3/32 in. T (Outwater Plastics Industries ALUZ5-M)

18-8 stainless steel knurled-head thumbscrews (slotted): 10-32 thread, 1 in. L, ¼ in. diameter head, ½ in. H (McMaster-Carr 91746A888)

18-8 stainless steel truss head Phillips machine screws (black-oxide plated, 25 count packs): 10-32 thread, ½ in. L (McMaster-Carr 94779A750)

18-8 stainless steel flat head Phillips machine screws (black oxide finish; 100 count packs): 8-32 thread, ¼ in. L, undercut (McMaster-Carr 96640A122)

18-8 stainless steel flat head Phillips machine screws (100 count packs): 10-32 thread, ¼ in. L, undercut head (McMaster-Carr 91771A825)

Testing

Wooden stretcher bars by Fredrix, 30 in. (76.2 cm) and 12 in. (30.5 cm) L

Cotton fabric

Animal hide glue

Chalk from Chamgagne, France, whiting, natural calcium carbonate (CaCO₃), supplied by Kremer Pigmente (247 West 29th Street New York, NY 10001)

Aluminum foil-faced expanded polyurethane board (polyshield sheeting/underlayment): 48 × 96 × ¼ in. T

Aluminum tape

Blotting paper

Silica gel

RECIPES (Massey 1967)

Animal hide glue solution

Ingredients

1 part powdered animal hide glue (115 g)

10 parts water (500 mL)

Preparation: Powdered animal hide glue (rabbit skin, cowhide, parchment, etc.) was soaked overnight, then warmed in a double boiler until fully dissolved.

Application: Warm glue solution was brushed over the cotton canvas. Two layers of size were applied to each sample.

Chalk ground (gesso)

Ingredients

2 parts chalk (see above specifications) (1180 g)

1 part animal hide glue solution (590 mL)

Preparation: Glue solution was warmed in a double boiler. Chalk was added a bit at a time, and solution was stirred to remove any lumps before adding more chalk.

Application: Warm gesso solution was brushed onto the canvas in one direction. Gesso was left to fully dry (usually overnight) before sanding. A second coat was applied in the opposite direction from the first coat, left to dry, then sanded. An average of two gesso layers was applied to each sample canvas.

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