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# Experimental tests for mechanical properties of wooden ‘buttons’ used for attaching auxiliary supports behind panel paintings

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**Abstract.** When wooden supports of panel paintings have been severely altered or damaged and the original crossbeams are missing, new crossbeams or other types of auxiliary supports can be connected to the panel’s back-face in order to achieve desired effects including panel strengthening and control of deformations. In order to make such connection, the Restorers of Opificio delle Pietre Dure use small wooden blocks, each glued on the back face of the panel, and holding freely the head of a screw connected (often by means of springs) to the auxiliary support; the English term ‘buttons’ has been proposed for such blocks. This research examines in depth how the shape (conical or cylindrical) and dimensions (diameter in the 20-30 mm range, and thickness in the 3-6 mm range) of the buttons, all made from oak wood, influence their stiffness and load-carrying capacity. Each button was glued onto a dummy beech board by means of epoxy structural resin; a 3 mm diameter steel screw was inserted in each button’s hole prior to gluing, so that its head remained ‘trapped’ between the button’s cavity and the board. A short-term mechanical test was performed with a universal testing machine by axially pulling out the screw from the button. Load and displacement were recorded, and the load–displacement curves were analysed. The results showed that within the tested range: a) the ultimate load-carrying capacity of the buttons is only influenced by the residual thickness above the screw head, b) nor the shape nor the external diameter of the buttons have any influence on their mechanical properties, c) the stiffness (slope of the straight part of the load-displacement curve) of the connection depends only on the embedding of the screw head into the wood (i.e. mainly on the wood density).

## 1. Introduction

When wooden supports of panel paintings have been severely altered or damaged and the original cross beams are missing, new cross beams or other types of auxiliary supports can be connected to the panel’s back-face in order to achieve desired effects including panel strengthening and control of deformations [1, 2, 3, 4]. In order to make such connection, several conservation laboratories use small wooden blocks, each glued on the back face of the panel and holding freely the head of a screw connected (often by means of springs) to the auxiliary support; being called in Italian ‘piedini’ or ‘bottoni’ [1, 2], the English term ‘buttons’ having been proposed for such blocks.



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A previous article [5], deals with an exploratory work useful to comprehend the basic mechanical behaviour of the buttons. The experimental plan was to test three different button shapes and four wooden species plus an MDF panel at standard humidity condition. The external geometry of the button was cylindrical and common for all the tested buttons; however, the hole trapping the flat screw was conceived counterbore and countersink. The counterbore hole were 2 or 3 mm deep and a washer was inserted in order to stiff the remaining wood and distribute the stresses on a surface instead of a hypothetical line, whereas the countersink hole guarantees a more distributed forces and are the quite typical manufacture of the restorers. The four wooden species were oak, beech, lime and walnut. The buttons were glued on poplar dummy boards by epoxy resin (type UHU Plus), in order to guarantee that the failure would not occur at the glue line. The buttons underwent pull out tests with a universal testing machine, a total of 105 were tested. Load and displacement data were recorded, and the load–displacement curves were analysed. The analysis of these mechanical tests leads to the following main observation: a) the rupture occurs beyond the proportional limit, thus all the buttons do not suddenly fail, and b) the geometry of the holes strongly influences the mechanical behaviour of the buttons, since the countersink buttons show a stronger, together with a more deformable, behaviour then the counterbore ones.

The research described in this second paper examines in greater depth how the external shape and dimensions (diameter and thickness) of the buttons, made from oak wood only, influence their stiffness and load-carrying capacity. In order to eliminate the influence of wood density, the specific stiffness and specific ultimate load are computed and analysed. The obtained results are intended to be useful for the practical conservators to design the auxiliary support system.

## 2. Materials and Methods

The buttons were made of oak wood (*Quercus petraea* (Matt.) Liebl), which is a species commonly used by the practical conservators. They are obtained from several planks with mean density of  $640 \text{ kg/m}^3$  ( $\pm 55 \text{ kg/m}^3$ , standard deviation) at standard conditions (65% of relative humidity and  $20 \text{ }^\circ\text{C}$ ) and nearly  $1.15 \pm 0.26 \text{ mm}$  (standard deviation) width of annual ring. The buttons were cut from quarter-sawn boards (i.e. to be loaded along the tangential direction) which were 7 mm thick. Before obtaining the buttons, the boards were equilibrated at standard conditions in a climatic chamber. The buttons had a countersink (90 degrees) geometry, with various combination of diameters and thicknesses (Figure 1a). Since 3 mm diameter screws with countersunk head (90 degrees) were used, the contact between the screw and the wood was approximately total but quite small. The external diameters were 20-25-30 mm, and the thicknesses were 3-4-5-6 mm; for each combination of diameter and thickness, at least 10 buttons were prepared and tested. In addition, a different-shaped button was tested (Figure 1b), this choice was made together with practical restorers who usually shaped the buttons as truncated cone; such shape helps them to mount the frame or the crossbar on the support. Indeed, usually the restorer glues dozens of buttons on the support as first operation, and then puts the crossbar or frame on the support trying to centre all the glued buttons. Typically, it is a complicated operation because some of the buttons might not be well centred on the respective crossbar holes; this is one main reason why the restorer needs to let a certain tolerance between the buttons and their corresponding holes, that gap is obtained thanks to the truncated-cone shape of the buttons and the holes. The other main reason for leaving some lateral gap between button and hole, is that when the panel swells or shrinks mainly transversally due to moisture content variations (modification of humidity and/or temperature of the surrounding environment the panel painting experienced) the distance between buttons may change slightly, whereas the distance between the holes remains constant since the longitudinal shrinkage/swelling of the cross-beam is negligible.

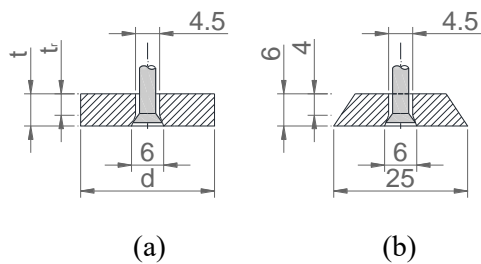


Figure 1 a) geometry of the cylindrical-shaped buttons, characterized by a countersink 2 mm deep with a total contact between the head of the screw and the wood; where  $d$  is the button diameter (15-20-25 mm approximately),  $t$  is the thickness (3-4-5-6 mm approximately) and  $t_r$  is the residual thickness; b) geometry of the truncated cone-shaped buttons, realized according to the measures here reported.

All the buttons, first equilibrated at standard humidity conditions were glued on 30 mm thick dummy beech boards by means of epoxy structural resin (type UHU Plus) like in [5], in order to guarantee that the failure would not occur at the glue line. A 3 mm diameter steel screw was inserted in each button prior to gluing, so that its head remained ‘trapped’ between the button’s cavity and the board. Then mechanical tests were performed with a universal testing machine to pull out the trapped screw and measure both the deformability and the strength of each button. The testing machine is equipped with a potentiometric transducer (virtually infinite resolution and linearity  $\pm 0.05\%$ ) to measure the displacement imposed longitudinally to the screw and a pressure transducer (error 0.198 % on FS= 4 kN) to measure the corresponding force the button underwent. The data were collected on a computer by means of a 12-bit USB card with an acquisition rate of 10 Hz and a digital resolution of  $\pm 0.018$  mm and of  $\pm 8$  N. The overall average error was  $\pm 0.068$  mm for the displacement and  $\pm 16$  N for the force measurements.

### 3. Results and Discussions

First, a direct observation of the buttons allows analysing the various failure types. Secondly, the data were plotted in a force-displacement graph to analyse the influence of the diameter and the residual thickness on both the ultimate load and stiffness of the buttons. However, the distribution of the specimens throughout the density and the thickness ranges is not uniform; in particular, the thinner specimens accidentally display lower density values. Therefore, in order to take into account the density effect on the test results, the Specific Stiffness (SSt) and Specific Ultimate Load (SUL) are computed and analysed.

In Figure 2, a typical load-displacement curve is presented to analyse the mechanical behaviour of the buttons, together with the image of the double-leaved door-like rupture as defined in [5]. The mechanical behaviour of the tested specimens is quite typical, with an elastic part component followed by a plastic one and finally the rupture [5]).

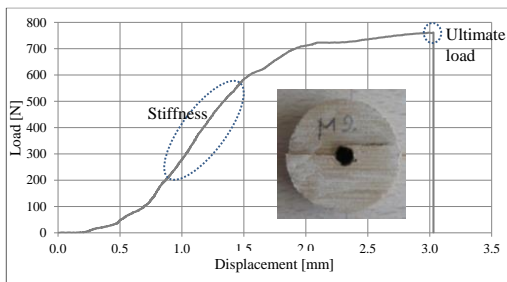


Figure 2 load-displacement curve of a specific tested button. Both the stiffness (the central slope of curve) and the ultimate load parameters are pointed out by dotted “circles”. The image of the failed button shows a typical double-leaved door-like rupture.

*3.1. The influence of the geometric parameters on the tested mechanical properties: the external shape*

Approximately ten buttons for each shape were tested, with the same diameter (25 mm) and residual thickness (4 mm approximately). In order to analyse the possible influence of the external shape of the buttons, the mechanical behaviour is observed, focussing on the ultimate load. For each mechanical test, the SUL of the load-displacement curves are plotted (Figure 3). The average SUL value is  $1.15 \text{ N m}^3 \text{ kg}^{-1}$  for cylindrical buttons (standard deviation is  $\pm 0.06 \text{ N m}^3 \text{ kg}^{-1}$ ) and  $1.18 \text{ N m}^3 \text{ kg}^{-1}$  for truncated cone buttons (standard deviation is  $\pm 0.06 \text{ N m}^3 \text{ kg}^{-1}$ ); such values confirm that no statistically significant difference in strength occurs. The same reasoning applies to compare the SSt between the two different shapes. In this regard, the average SSt is  $1.14 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$  for cylindrical buttons (standard deviation is  $\pm 0.25 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$ ) and  $1.52 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$  for truncated cone ones (standard deviation is  $\pm 0.43 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$ ). The boxplots (Figure 3) illustrate the values above mentioned, showing no statistically significant differences between the two different shapes for the investigated mechanical properties. It is an expected result; indeed, the fracture starts under the screw head and develops along a specific diameter, or surface, of the button. It is a simplified and qualitative explanation of the fracture mechanics; however, it clarifies the negligible influence of the external shape. Since the external shape of the buttons does not affect the strength, this work could focus on the cylindrical shape only, which data are easier to be processed. Of course, the results and comments also apply to the truncated buttons.

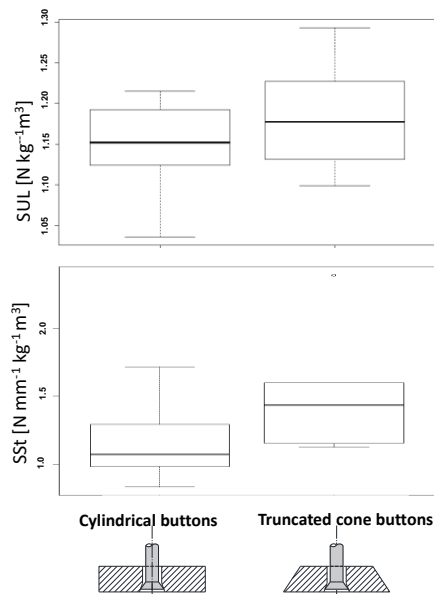


Figure 3 The values of the ultimate load and stiffness for both the cylindrical and truncated cone buttons are presented to confirm that the shape does not affect the buttons' mechanical behaviour; indeed, no statistically significant difference is observed for the two types of buttons.

### 3.2. The influence of the geometric parameters on the mechanical properties: the diameter

The mechanical properties here investigated are the specific ultimate load and the specific stiffness of such buttons as function of the variable diameter; for this purpose, several buttons with three different diameters (20, 25 and 30 mm) and the same thickness (6 mm) are tested and the results are shown in Figure 4.

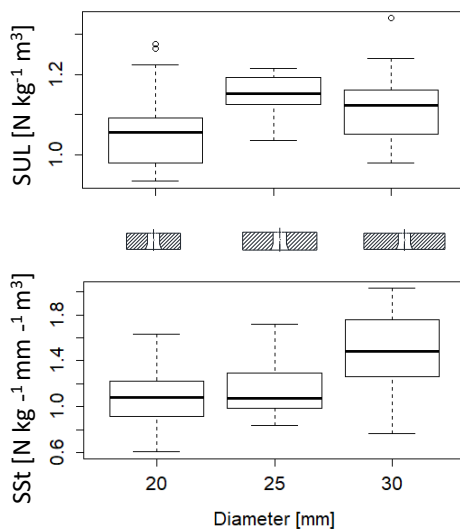


Figure 4 The boxplots illustrate the influence of the diameter on the mechanical properties of the buttons. The graphs shows no statistical significant difference for the tested specimens. The three outliers (represented by small circles) in the ultimate load graph are here reported for completeness, however

they correspond to tests in which the crosshead speed was accidentally too high, and should not be considered in the analysis.

The boxplot on the SUL highlights a certain homogeneity of the load-bearing capacity related to the various diameters. The differences observed are not statistically significant and the computed average value is  $1.11 \text{ N m}^3 \text{ kg}^{-1}$  ( $\pm 0.10 \text{ N m}^3 \text{ kg}^{-1}$ , standard deviation). Analysing the boxplot on the SSt, once again, no statistically significant differences are observed for the force values related to the diameter; the average value is  $1.25 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$  ( $\pm 0.38 \text{ N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$ , standard deviation). The graphs shows no statistical significant difference for the tested specimens. The three outliers (represented by small circles) in the ultimate load graph are here reported for completeness, however they correspond to tests in which the crosshead speed was accidentally too high, and should not be considered in the analysis. In Table 1, the mean value for each tested diameter is listed together with the standard deviation. The data confirm that no statistically significant differences is evident. These tests point out that the diameter does not influence the mechanical properties of the buttons, and therefore the restorers may choose any dimension for such parameter among the studied values, according to their needs.

Table 1 The means and their standard deviations of both the SUL and SSt for 3 different button diameters.

	SUL [ $\text{N m}^3 \text{ kg}^{-1}$ ]	SSt [ $\text{N m}^3 \text{ mm}^{-1} \text{ kg}^{-1}$ ]
Diameter 20 mm	$1.07 \pm 0.11$	$1.06 \pm 0.28$
Diameter 25 mm	$1.16 \pm 0.06$	$1.29 \pm 0.37$
Diameter 30 mm	$1.18 \pm 0.09$	$1.46 \pm 0.40$

### 3.3. The influence of the geometric parameters on the mechanical properties: the residual thickness

The residual thickness ( $t_r$ , Figure 1) is the remaining wood thickness above the head of the screw. Once again, the mechanical properties here analysed are the specific ultimate load and the specific stiffness. The tested buttons had the same diameter (25 mm) and four different thicknesses (3, 4, 5 and 6 mm approximately). The results (Figure 5) highlight a clear influence of the residual thickness on the specific ultimate load, which is higher for the greater thicknesses.

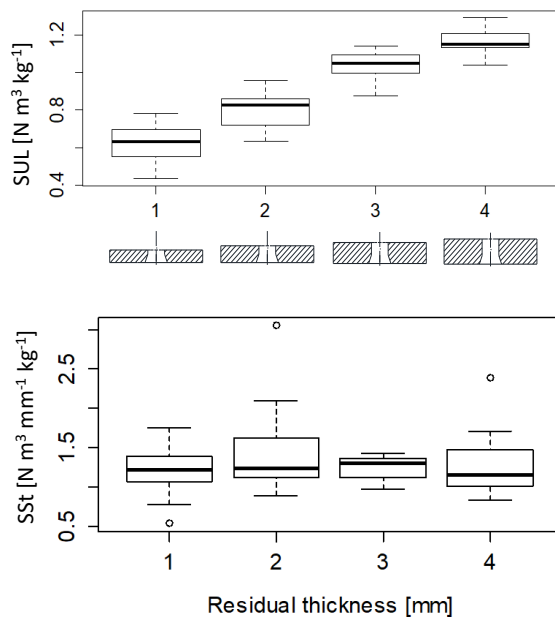


Figure 5 The boxplots illustrates the influence of the residual thickness on the mechanical properties of the buttons. The graphs shows a significant difference when the residual thickness is taken into account, according to specific ultimate load (SUL, top of figure); on the contrary no effect of residual thickness on specific stiffness (SSt, bottom) is observed.

In Table 2 the mean values of SUL and SSt are listed for each residual thickness, together with the related standard deviation. Focussing on the specific stiffness, no significative differences are observed (Figure 5). This confirms that the stiffness property does not depend on the dimensions of the buttons, i.e. not on the diameter neither on the residual thickness, since it simply depends on the innate material properties of the wood of which the buttons were made.

Table 2 The means and their standard deviations of both the SUL and SSt over 3 different residual thicknesses.

	SUL [N m <sup>3</sup> kg <sup>-1</sup> ]	SSt [N m <sup>3</sup> mm <sup>-1</sup> kg <sup>-1</sup> ]
Residual thickness 1 mm	0.63 ± 0.10	1.24 ± 0.34
Residual thickness 2 mm	0.80 ± 0.09	1.40 ± 0.47
Residual thickness 3 mm	1.04 ± 0.08	1.25 ± 0.15
Residual thickness 4 mm	1.15 ± 0.06	1.15 ± 0.26



### 3.4. The failure types

The failure types were strictly related to the residual thickness and it was possible to group all the tested buttons in two main groups, one gathering the thinner buttons (3 and 4 mm thick, residual thickness 1 and 2 mm respectively) and the other one gathering the thicker buttons (5 and 6 mm thick, residual thickness 3 and 4 mm respectively). The thinner buttons showed a typical failure type named “breakthrough-type” because the screw simply comes out the button without a real breaking (Figure 6). The thicker buttons, instead, underwent a clear failure because a piece of wood came off the buttons causing a rectangular-shape or ring failure type (Figure 6). The failure of the thinner buttons could not be considered as a real failure, it is more like a breakthrough due to the little residual thickness. On the other hand, the thicker buttons underwent a real failure with a clear detachment of some parts of wood. The rectangular-like and ring-like failures are the most common types observed for the thicker buttons, which occur at the large vessels level of the spring wood. It is a weakness surface, which sometime cuts across the large rays typical of oak wood.

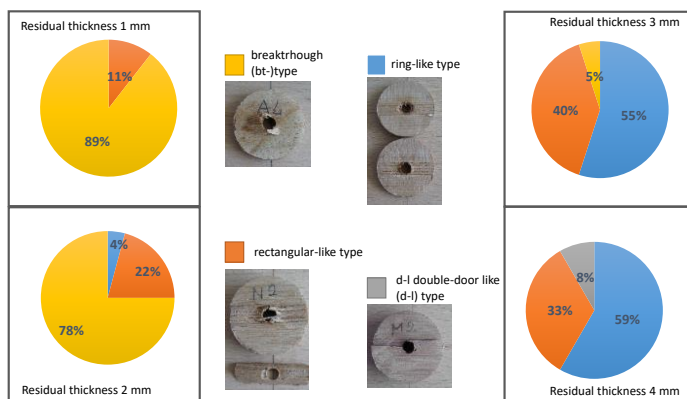


Figure 6 The pictures in the central area show the four failure types observed during the experimental tests: breakthrough type (in yellow), rectangular-like type (in orange), ring-like type (in light blue) and d-l double-door-like type (in grey). The outlying pie charts show the distribution of the failure types according to the residual thickness: the breakthrough-like failure is predominant for the thinner buttons; otherwise, the rectangular and ring-like failures are typical for the thicker ones.

### 3.5. Hypothesis on the causes resulting in the failure of the buttons

The failure mechanism is quite complex since it involves various phenomena that are here described by means the observation of the failure surfaces. At the beginning of the mechanical test, the prevalent phenomenon occurring is the embedding of the screw head into the wood. It is a common mechanism for all the buttons, which is independent from diameter or thickness. It is the prevalent mechanism, which causes damage of the buttons. The embedding, also, strongly affects the proportional part of the load/displacement curve, which determines the stiffness value; that is why no significant differences are observed among the buttons. When the load increases, the thinner buttons (1 and 2 mm residual thickness) fail for the screw head breaking through the wood. On the other hand, the thicker buttons fail for higher load values (Table 2) because the rupture involves a combination of other mechanisms. The cleavage (along the grain) is involved, in combination with the tension perpendicular to the grain, when a whole ring detaches from the button and the rolling shear (across the grain), when a rectangular-like failure occurs. Such mechanisms show up in the proximity of the screw head and trigger off the failure, which later propagates along the grain. As just explained, all these phenomena (embedding, perpendicular-to-the-grain tension, rolling shear and cleavage) occur in the wood around the head screw; which again explains why the tested diameters do not affect the mechanical properties of the buttons.

#### 4. Conclusions

This research focuses on the mechanical behaviour of oak buttons characterised by various diameters and thicknesses, to analyse the influence of such dimensions on the specific ultimate load and specific stiffness. The results give some practical information, which could be useful for the restorers who use the buttons to attach the crossbar to the back face of the panel.

The following main observations are here summarized:

- all the mechanical phenomena which caused the failure are localised around the head of the screw, thus:
  - a) the diameter does not influence the ultimate load;
  - b) the residual thickness is the only variable which influences the ultimate load;
  - c) nor the diameter of the button neither the residual thickness have any influence on the stiffness, which is comparable for all the tested buttons, and depends only on the embedding of the screw head into the wood;
- the observed failure mechanism is different for the thinner (1-2 mm residual thickness) and thicker buttons (3-4 mm residual thickness), since the former failure is the result of the breaking of the screw through the thickness of the button and the latter is mainly caused by cleavage together with rolling shear and tension perpendicular to the grain;
- no influence of the external shape has been observed on the analysed mechanical properties.

The following practical suggestions derive from the above observations: a) the ultimate load is only influenced by the residual thickness above the screw head, b) the external diameter of the buttons has no influence on their mechanical properties. Finally, since the external shape (cylindrical or conical) has no influence on the mechanical properties, the restorers may choose it according to their needs.

As a future work, it will be of interest to develop a numerical model able to interpret the button failure behaviour, which is only a hypothesis at the moment.

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