ANALES de Edificación

Received: 15/10/2021
Accepted:28/10/2021

Anales de Edificación
Vol. 7, Nº3, 10-19 (2021)
ISSN: 2444-1309
Doi: 10.20868/ade.2021.4970

Determinación de las propiedades de flexión del contrachapado de lauán mediante ensayos de flexión por compresión
Determination of bending properties of lauan plywood by compression bending tests

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Resumen-- **Las propiedades de flexión de la madera contrachapada generalmente se obtienen a partir de pruebas estándar de flexión de 3 o 4 puntos. Estos ensayos han sido ampliamente cuestionados debido a la influencia del método de medición de la deflexión y debido a la concentración de tensiones en las proximidades del área de contacto de la muestra con el dispositivo de carga. Algunos autores han propuesto el uso de ensayos de flexión por compresión para estos fines. Pero los resultados relacionados con la resistencia son más bajos de lo esperado e incluso más bajos que los de la prueba de flexión de 3 puntos. En este artículo, describimos algunas soluciones, como aumentar la longitud de las muestras y determinar la resistencia, incluidos los efectos de la tensión a la compresión, y no solo a la flexión. En este sentido, se realizaron ensayos de flexión por compresión para medir las propiedades de flexión -resistencia y módulo de Young- de contrachapados de lauan de 9 y 12 mm. Finalmente, los resultados de las pruebas se comparan con los valores del Estándar Agrícola Japonés (JAS) para madera contrachapada para verificar la aplicabilidad.**

Palabras clave— lauán; madera contrachapada; ensayo de flexión por compresión; resistencia a la flexión; El módulo de Young.

Abstract— **The bending properties of plywood are usually obtained from standard 3 or 4 points bending tests. These tests have been thoroughly questioned because of the influence of the deflection measurement method and because of the stress concentration in the vicinity of the specimen contact area with the loading fixture. Some authors have proposed the use of compression bending tests for these purposes. But the results concerning strength are lower than expected and even lower than those from 3 points bending test. In this paper we outline some solutions like to increase the length of the specimens and to determine the strength including compression, and not only bending, stress effects. In this sense, compression bending tests were conducted to measure bending properties -strength and Young's modulus- of 9 and 12mm lauan plywood. Finally, tests results are compared with values from Japanese Agricultural Standard (JAS) for plywood in order to check applicability.**

Index Terms— lauan; plywood; compression bending test; bending strength; Young's modulus.

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I. Introduction

The trade group of wood species designated by the name lauan constitutes a large percentage of the total amount of hardwood plywood imported to Japan (where it is probably the most widespread group in building) and the United States of America (Ainsworth, D. 1995). Among the four commercial subgroups under which it is distributed -dark red, light red, white and yellow lauan-, light red is the most expanded one, since it includes the species Shorea parvifolia and Shorea macroptera, both listed as "Least concern" category in version 3.1 of the IUCN (International Union for Conservation of Nature) list.

As lauan plywood is a material used in building structures, it is necessary to specify the mechanical properties to guarantee its use following sectoral safety standards. The most common protocol for determining the bending properties of plywood is the 3- or 4-point bending test. Nevertheless, some authors - Uemura 1984 (ASTM D790), Fukuda (1989) and Yoshihara (2001)- have questioned the suitability of 3- and 4-points bending tests as a means for the characterization of anisotropic materials, such as wood or wood-derived products. Even when these tests are conducted following the guidelines of UNE-EN 408 (these authors worked with ASTM D790-71), stress concentration occurs in the vicinity of load application zone. This stress concentration depends on the shape and material of the loading nose and causes that tests strength results are lower than the real ones.

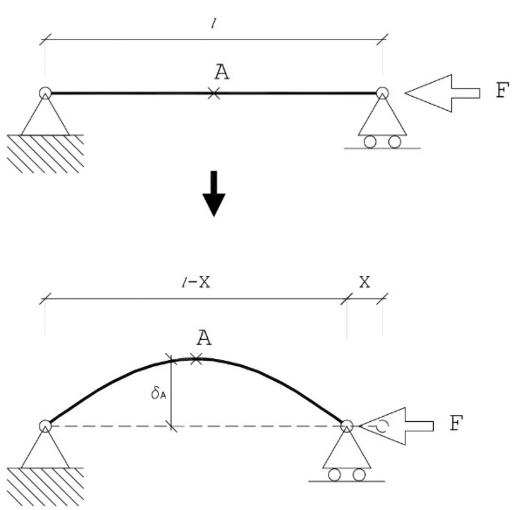

Fig. 1. Compressive bending test scheme.

As a solution to this phenomenon, Fukuda himself proposes a new test method (Fig. 1.) that avoids contact during the application of the transverse load: specimens are compressed axially, buckle, and deform until they break around midpoint.

II. Theoretical approach

A. Materials

In this new test method, specimen is flexo-compressed and bending stress on both faces at the midpoint A is the result of the sum of two components: the one caused by bending - eccentricity - and the one caused by compression. Therefore, the following equation is used to calculate the total stress:

$$\sigma_m = \frac{M_A}{W} \pm \frac{F}{A} = \frac{6F\delta_A}{bt^2} \pm \frac{F}{A} \qquad (1)$$

This expression indicates the different possibilities of specimen rupture. When bent, convex part of specimen is tensioned, and concave part is compressed. If failure occurs before compressive stress reaches the proportional limit stress, plastic deformation does not appear in the compressed part, and the rupture is brittle and in the stretched part. This behavior corresponds to failure mode 1 of the four described in Buchanan (1990). In this case, the mathematical expression for bending strength would be:

When specimens fail in Buchanan's modes 2, 3 or 4, the stress

$$f_{m,0} = \frac{6F\delta_A}{bt^2} - \frac{F}{A} \qquad (2)$$

distribution at failure is governed by plastic deformation on the compressed face. To maintain the equilibrium of stress volumes, the tensile stress must be greater than the compressive stress, so estimating the bending strength during elastoplastic stages as the value of the compressive stress is conservative and on the safe side. That is, from the moment at which the compressive stress reaches the proportional limit - defined as the point at which the ratio εt/εc ceases to be linear -, bending strength is derived by:

The values for geometrical parameters of specimen (where b

$$f_{m,0} = \frac{6F\delta_A}{bt^2} + \frac{F}{A} \qquad (3)$$

stands for width and t for thickness) and the values for applied force, F, and deflection, δ_A, are needed to compute this equation. While the measurement of geometrical concepts is immediate, obtaining the last two magnitudes is not trivial since they progress throughout the test and some clarifications must be done.

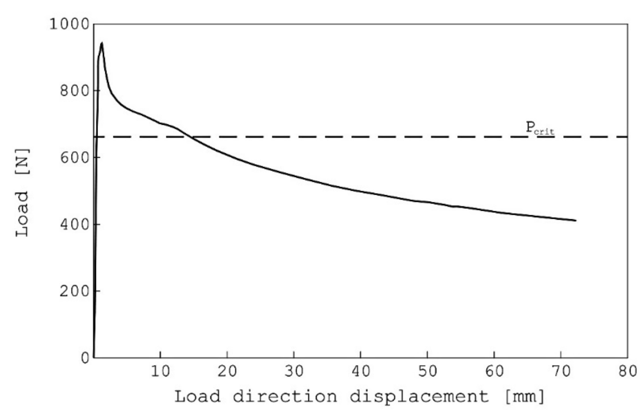

Fig. 2. Compressive bending test scheme.

Fig. 2. shows the load-displacement curve in load direction. The curve has its maximum in the form of a peak, from where it drops sharply to a value closer to Euler's critical load, and then descends with a constant slope. The maximum point corresponds to the displacement of the end X that produces a deflection equal to the half-thickness of specimen. The excess

with respect to Euler's critical load can be understood as the overload that is necessary to apply to initiate buckling. One of the causes of this excess can be found in the force that must be applied to overcome static friction factor between the elements that make up the joint. But microscopic structure of wood also plays its role. If we consider wood fibers as a set of interconnected longitudinal rods, most of libriform and tracheid fibers must buckle to allow specimen to start to bend. These longitudinal fibers do not have the exact alignment of the whole, but are distorted by the passage of radial cells, causing initial twists and/or eccentricities. The buckling of some of these fibers is opposite to the buckling of the whole specimen and involves an extra amount of energy that is expressed as an increase of the load for buckling initiation.

When the end of specimen where the load is applied is displaced longitudinally by X value, the midpoint of specimen moves X/2. Therefore, the sensor that records the deflection, δA, must move together with the midpoint of specimen in the direction of load application throughout the test. Since the expected longitudinal and transverse displacements are large (around 15% and 30% of the length, respectively), the use of LVDT (Linear Variable Differential Transformer) sensors becomes complicated. However, it is possible to derive δA mathematically, by solving the second order differential equation that represents the deformation equation. Lienhard (2014), proposes the following expression as a solution:

$$\Delta\delta_A = \sqrt{\frac{(L-l_1)\cdot 3\cdot l_1}{8}} - \sqrt{\frac{(L-l_2)\cdot 3\cdot l_2}{8}} \quad (4)$$

where ΔδA is the deflection increment, which is a function of L, the total length of the specimen and l1 and l2, the initial and final span values whose variation generates the deflection.

On the other hand, Yoshihara, 2001, uses the following solution:

$$\delta_A = \begin{cases} 0.620\cdot l\cdot\left(\frac{X}{l}\right)^{0.50} & \left(0 \le \frac{X}{l} < 0.1\right) \\ 0.505\cdot l\cdot\left(\frac{X}{l}\right)^{0.40} & \left(\frac{X}{l} \ge 0.1\right) \end{cases} \quad (5)$$

$$\delta_A = \begin{cases} 0.620\cdot l\cdot\left(\frac{X}{l}\right)^{0.50} & \left(0 \le \frac{X}{l} < 0.125\right) \\ 0.505\cdot l\cdot\left(\frac{X}{l}\right)^{0.40} & \left(\frac{X}{l} \ge 0.125\right) \end{cases} \quad (5')$$

Both options have been drawn in Figure 3, together with the curve resulting from FEM computer simulation of the elastica of a 'pin-jointed' strut, which is taken as a reference for the relationship between distances. Yoshihara's solution is more accurate to what happens in FEM model. However, for values in the range 0.1≤(X/l)<0.125, a divergence is identified between the curve of mathematical expression and the one reflected by simulation. It is possible to mitigate this deviation by using in that range the first expression instead of the second, so that the solution used would be (5').

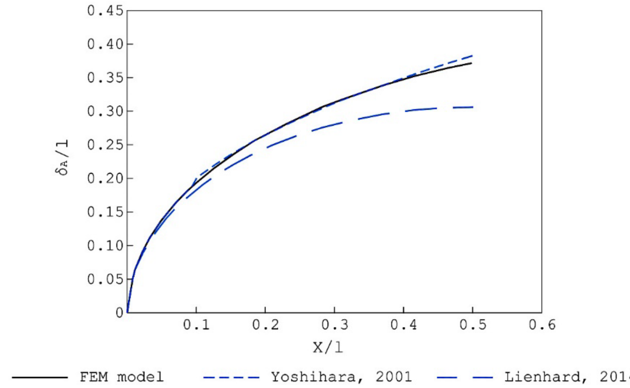

Fig. 3. Relationship between δA/l and X/l..

The second mechanical property to be determined by compression bending test procedure is the flexural modulus of elasticity. Assuming the hypothesis of plane deformation of the section (generalized Bernouilli-Navier's hypothesis), and that equilibrium exists between tensile and compressive stress volumes, the apparent flexural modulus of elasticity Em,0 is derived according to the following expression taken from Baño (2012):

$$E_{m,0} = \frac{4\cdot E_{t,0,m}\cdot E_{c,0,m}}{\left(\sqrt{E_{t,0,m}}+\sqrt{E_{c,0,m}}\right)^2} \quad (6)$$

where $E_{t,0,m}$ and $E_{c,0,m}$ are the values of tensile and compressive modulus of elasticity obtained in compression bending test. For this purpose, strain gauges must be installed at the midpoint of both faces to measure deformations. The expressions of this intermediate process are analogous to those proposed in tensile and compression tests of UNE-EN 789, except that data are obtained from compression bending test. Similarly, the values with subscripts 1 and 2 correspond, respectively, to 10% and 40% of the maximum of each magnitude.

$$E_{t,0,m} = \frac{\sigma_{2,t,0,m}-\sigma_{1,t,0,m}}{\varepsilon_{2,t,0,m}-\varepsilon_{1,t,0,m}} \quad (7)$$

$$E_{c,0,m} = \frac{\sigma_{2,c,0,m}-\sigma_{1,c,0,m}}{\varepsilon_{2,c,0,m}-\varepsilon_{1,c,0,m}} \quad (8)$$

B. Set up

Compression bending tests were carried out using a specifically designed configuration mounted on a structural testing frame (Fig. 4). The installed elements are, from left to right: reaction profile, load cell, joint, specimen, joint, linear displacement trolley, and hydraulic actuator. The load is introduced by means of a servo-controlled hydraulic cylinder Tomoe 200kN500st, with a capacity of 200kN, and the load cell used is TCLZ-2KNA model of Tokyo Sokki Kenkyujo brand, with a capacity of 2kN and an accuracy of 0.5N.

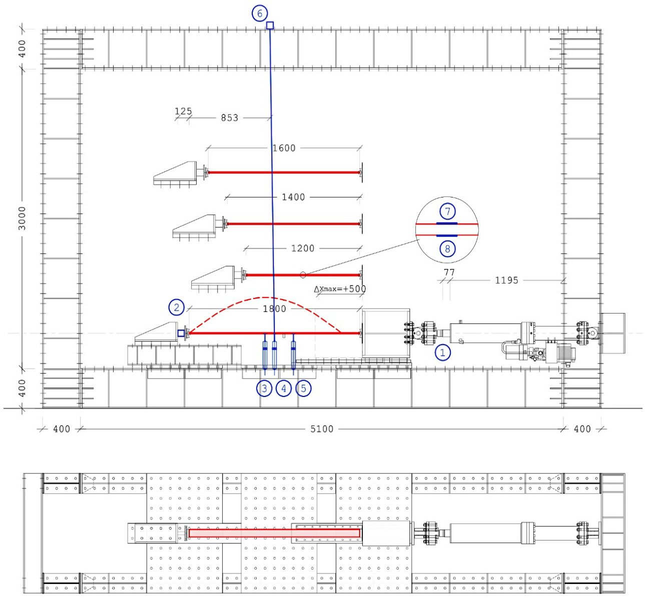

Fig. 4. Compression bending test set up.

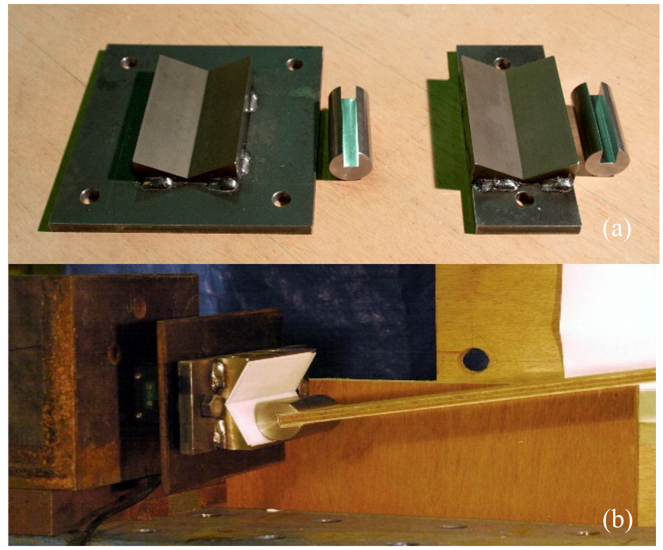

Fig. 5. V-notched and cylinder attachments designed for the materialization of test: (a) pieces manufactured by Tokyo Institute of Technology material service; (b) arrangement of joint elements and Teflon sheet.

The way of supporting hydraulic actuator and applying load -the end of cylinder is a pin joint- allows that force direction can rotate in relation to specimen direction. To ensure alignment of load and specimen, test setup is horizontal, which allows the installation of a loading trolley. This trolley moves in a straight line along the path of rails, and ensures that force, displacement, and specimen direction match. However, when the trolley starts to move on the rails, a non-negligible friction must be overcome, and the force recorded by hydraulic cylinder does not correspond to that applied to specimen. This motivates the introduction of a load cell just after specimen support, to measure actual reaction. Although rails were carefully lubricated, the difference between the notation of actuator and that from load cell is 0.3kN, which is the value for bearing friction.

When Fukuda (1989) designed the compression bending test, fiber-reinforced polymer specimen was inserted directly into V-shaped supports. In the test reproduction made by Yoshihara 2001, the edges of the wood-derived product specimens - with a lower fc,90/fc,0 ratio - split and collapsed in the area close to the ends. To overcome this difficulty, Yoshihara proposes a joint formed by two elements: Fukuda's V-shaped piece and a new cylindrical piece where each end of specimen is inserted. To facilitate the rotation of the cylinder, a Teflon sheet is included between both pieces. Due to the similarity of the mechanical properties of the plywood to be analyzed in this research work, it was decided to replicate Yoshihara's solution for the joint (Fig. 5.).

The specimens were tested at two, seven or 28 according to the European standard EN 196-1:2016. The average value recorded from six hemi-specimens is taken.

Tests were carried out with control of piston displacement speed, and not of applied force. The displacement of the moving end of specimen has a constant speed until failure in a lapse of time of 300 ± 120s.

TABLE I
INSTALLED SENSORS FOR COMPRESSION BENDING TEST

Sensor number	Sensor type	Model	Measured magnitude [unit]
1	Hydraulic actuator	Tomoe 200kN500st	Hydraulic piston displacement [mm]
2	Load cell	Tokyo Sokki Kenkyujo TCLZ-2KNA	Reaction. Force applied to specimen at support [N]
3	LVDT	Tokyo Sokki Kenkyujo CDP-100	Specimen central points deflection. At l/40 on the left [mm]
4	LVDT	Tokyo Sokki Kenkyujo CDP-100	Specimen central points deflection. Midpoint [mm]
5	LVDT	Tokyo Sokki Kenkyujo CDP-100	Specimen central points deflection. At l/40 on the right [mm]
6	Wire transductor	Tokyo Sokki Kenkyujo DP-1000E	Specimen midpoint deflection [mm]
7	Strain gauge	Kyowa KFG-20-120	Midpoint deformation. Tensioned face [-]
8	Strain gauge	Kyowa KFG-20-120	Midpoint deformation. Compressed face [-]

C. *Specimen description*

The cross-section of tested JAS Class 1 B-C lauan plywood specimens was defined by the thickness of tested boards, 9 and 12 mm, and a constant width of 72 mm. With this width, ratio between both dimensions (1/6 and 1/8) guaranteed the buckling in monitored direction. The length of specimens is variable, at 200mm intervals, with dimensions between 1200 and 1800m. To account for the effects of slenderness, the range of lengths was extended for 12mm plywood, with dimensions ranging from 600 to 1800mm. The adopted protocol included the testing of three specimens for each board length and thickness (Fig. 6).

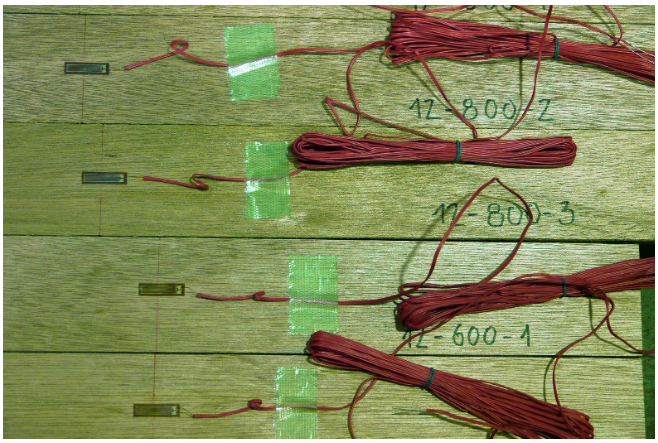

Fig. 6. Placement of strain gauges on some of the specimens

III. RESULTS AND DISCUSSION

Specimens collapse depends on the presence of defects or discontinuities in the layers that build up the board. Depending on their existence, importance, and location, three modes of failure are differentiated. The first mode of failure is the most generalized, since it is present in 67% of the sample, and implies the lack of important defects in the specimen. So, plastic deformation appears in the compressed concave part, and the tensile stresses increase successively until failure. For geometric slenderness between $50 < l/t < 100$, this is the only mode of failure observed, and involves the failure of the outer tensile layer, which drags the next layer inward, with transverse orientation (Fig. 7). For specimens with a longer length, this mode is mixed with the other two failure modes, and when occurs, it affects all layers -or all but the outer compressed one.

In the case of defects appearance only in the compressed half -either a discontinuity in the transverse layer or a defect in the outer one- a plastic hinge is formed, and specimen behaves like a three-hinged arch. If specimen fails in this mode, the strength calculated according to equation (3) is lower than the real one, and the error is greater the farther the hinge is from the central part. Since elastic modulus is calculated below 40% of load, its calculation is not affected either by the material yielding or the failure mode.

In the last failure mode, significant defects appear in the central third of both faces, so it is impossible to prevent the tensile face from being affected and its failure is brittle and in the convex face. During the test, a cracking sound is heard, which means that bending strength perpendicular of the grain has been exceeded in the vicinity of the knot, and partial breakage of specimen begins. This micro-breakage causes the lack of continuity of fibers on the tensioned part and the reduction of strength properties of cross section at that point, so it leads to a hinge similar to that generated when the defect is only on compressed face. The moment at which cracking sound is heard represents the onset of failure, so that specimen strength is the one that corresponds to the tensile stress at that instant. Only 6% of tested specimens failed in this mode, and they correspond to those with the lowest strength values.

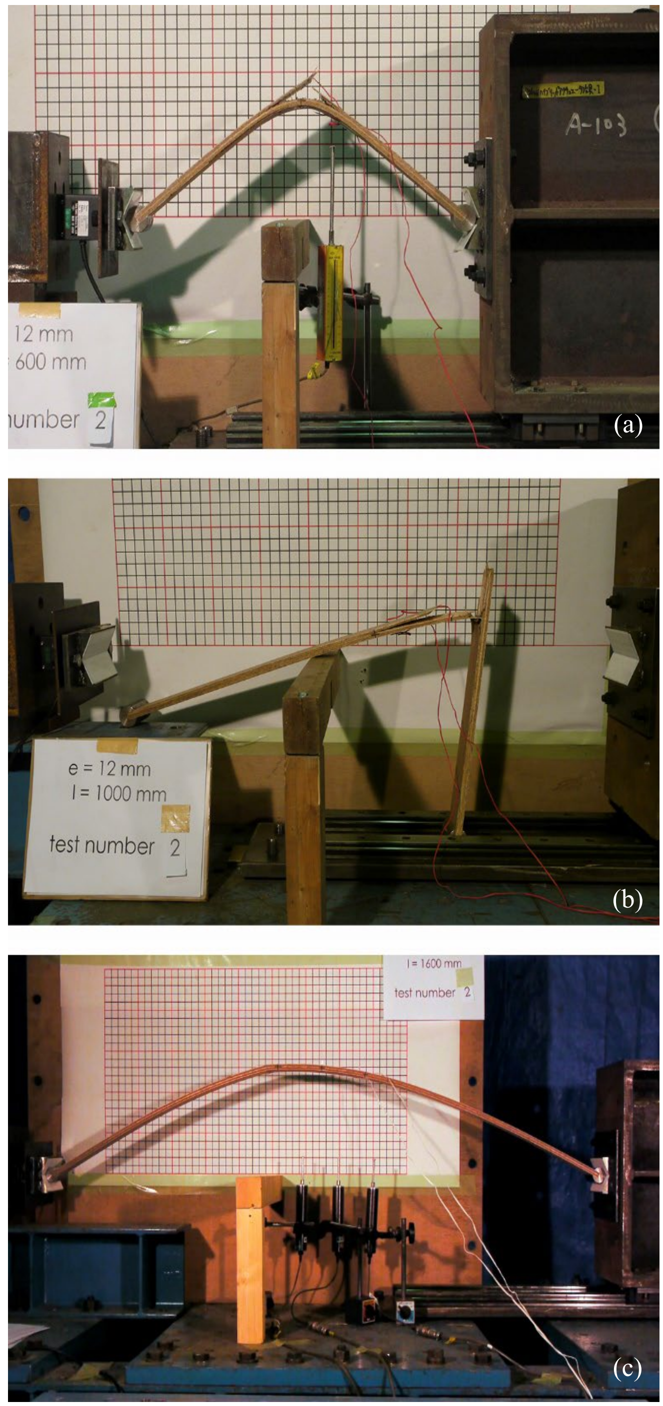

Fig. 7. Failure mode with plastic deformation at compressed zone: rupture affects the two outer layers (a), the four outer layers (b), and hinge formation (c).

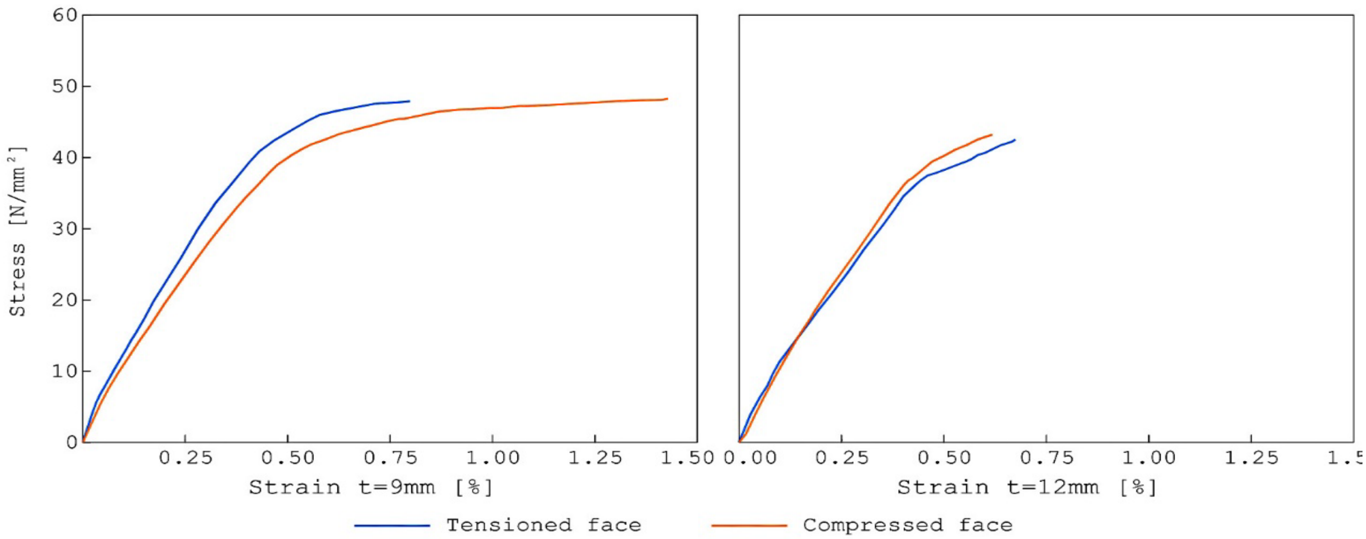

Fig. 8. Stress-strain diagrams of 9mm (left) and 12mm (right) thick plywood specimens.

Fig. 8. shows stress-strain diagrams for compression bending test of 9 and 12mm thick plywood specimens. They correspond, respectively, to specimens identified as 9_1800_3 and 12_1800_2. Two criteria have been followed for the selection of specimens representing each thickness sample. First, the ratio between tensile elastic modulus and compressive elastic modulus resulting from compression bending test (Et,0,m/Ec,0,m) must be equal to the mean value of the whole sample. In addition, the mode of failure of both specimens must be identical and include plastic deformation of the compressed zone.

If elastoplastic phase of the curves, which does not affect the calculation of elastic modulus, is neglected and comparison is focused only on the elastic phase of both diagrams, it is observed that the behavior of average specimen of 12mm thick plywood differs from that of 9mm. 9mm thick specimen shows two well differentiated curves. The slope of curve of tensile face is higher than that of compressed face, and ratio between both elastic moduli is 1.16, which equals the ratio between average values of elastic moduli obtained in specific compression and tensile tests. However, the behavior of 12mm thick specimen is different from that of 9mm specimen, and also different from the expected one. The curves of tensile and compressed faces run so close, or even compressive elastic modulus is higher than tensile modulus.

The justification for this disparity lies in the initial curvature of specimens. 9mm thick plywood slats arrived to the laboratory with a previous deformation, most probably caused by hygrothermal variations suffered during their storage in the factory or carpentry workshop. The magnitude of this deflection was quantified in values between 1/250 and 1/65. This initial eccentricity was sufficient to make that, when compressed longitudinally, 9mm slats began to buckle directly, without the need for a previous phase to generate the bending. However, 12mm thick plywood specimens arrived without any initial deformation, or with negligible camber (deflection lower than 1/800). In the lack of prior deformation, the specimens are compressed until they reach the critical load that initiates buckling in transverse direction. This means that, assuming specimen is completely flat, even the face that will later be tensioned starts being compressed.

To avoid the natural deflection that specimens would have due to their own weight, an intermediate support was installed to reduce the span around central part (midpoint was occupied with a linear displacement sensor). This support also ensured specimen to buckle towards the side where monitoring had been prepared, as well as protecting the measuring devices installed below. Despite the careful treatment taken in the arrangement of the central support to ensure alignment with specimens ends, the interaction between intermediate support, initial curvature and curvature caused by its own weight, cause that, in the phase of load entry prior to buckling, alternative deformations with greater complexity are generated, until the slat snaps to the lowest energy shape, and begins to bend according to the elastic of a sinusoidal arch (Fig. 9.). While specimen adopts one of these more complex deformations, tensile stresses may appear on the face that will later be compressed. These tensile distortions in the pre-buckling phase are the reason why, in 12mm thick plywood specimens, the slope of the tensile curve is greater than, equal to, or lower than the compressive curve.

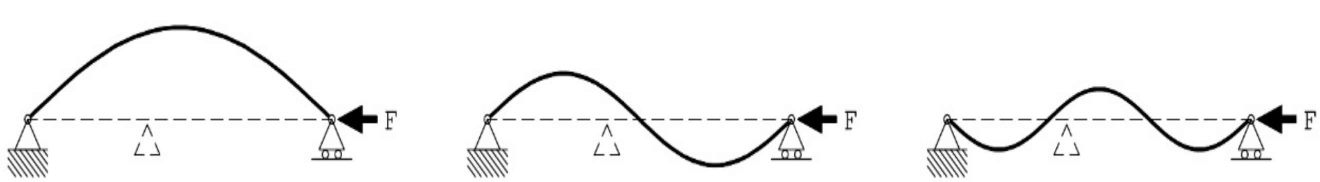

Fig. 9. Different elasticas can be compatible with the same boundary conditions.

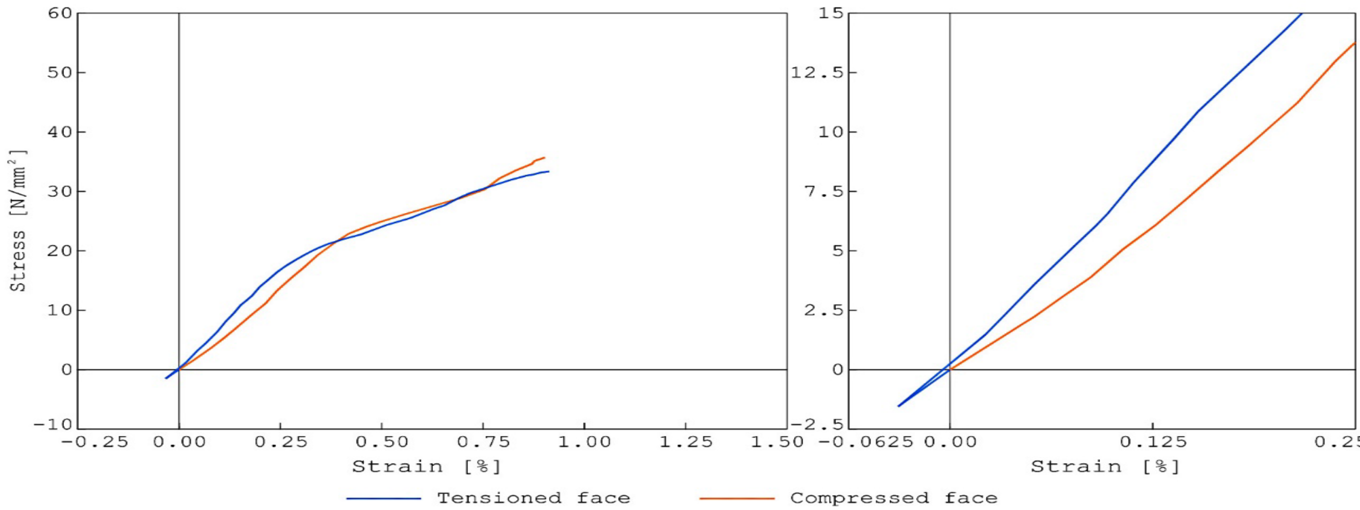

Fig. 10. Stress-strain diagram of specimen 12_600_1: overall view (left) and start detail (right)..

In the case that both ends, and midpoint of specimen are aligned in its original state, and the first deformation adopted after buckling is the simplest, the result of compression bending test shows a higher tensile elastic modulus than the compressive one, as expected. This happens, for example, in the specimen identified as 12_600_1, whose stress-strain diagram is shown in Figure 10. In addition, since it is a specimen of shorter length, the critical force is greater and the process prior to buckling is better distinguished. It can be seen in the detail of the diagram that the start of the curve corresponding to tensioned face has the same slope as that of compressed face, since, theoretically, specimen is in simple compression until it begins to buckle. Once the specimen eccentricity exceeds plywood semi-thickness, the tensile curve abruptly changes slope, passing from compressive elastic modulus slope to follow the tensile one. The ratio Et,0,m/Ec,0,m obtained for this specimen is 1.16, coinciding with the ratio of elastic moduli resulting from the specific tensile and compression tests (Et,0/Ec,0) carried out for this purpose.

All the reasons explained above make that the variability of the results for bending Young's modulus of 12mm thick plywood is very high, while 9mm sample is more homogeneous (Fig. 11.). The coefficient of variation obtained for 12mm thick sample is 21%, very close to 22%, that is the average value of the coefficient of variation that 'Wood Handbook' -Forest Product Laboratory of Madison (1999)- details for the elastic modulus in bending tests. However, the coefficient of variation of 9mm thick plywood group is 10%. Since no specimen sample exceeds 'Wood handbook' limit, no correction was necessary and both groups are considered statistically representative.

In tensile or compression tests, plywood layout -if assumed to be symmetrical- has no influence on stiffness calculation, and only depends on the amount of material arranged with grain parallel to the load. But in bending test the thickness and layer distribution are very relevant. The difference between test values and those given in JAS standard (Table 2) comes from the freedom that the standard gives to plywood manufacturer. The value defined in JAS standard corresponds to the minimum required and is calculated by using the minimum thickness for layers with grain running parallel to longitudinal direction and maximum thickness for the ones in the perpendicular direction. Therefore, the increments between test results, where actual plywood have been used, and those of JAS standard, computed from extreme theoretical boards, are logical.

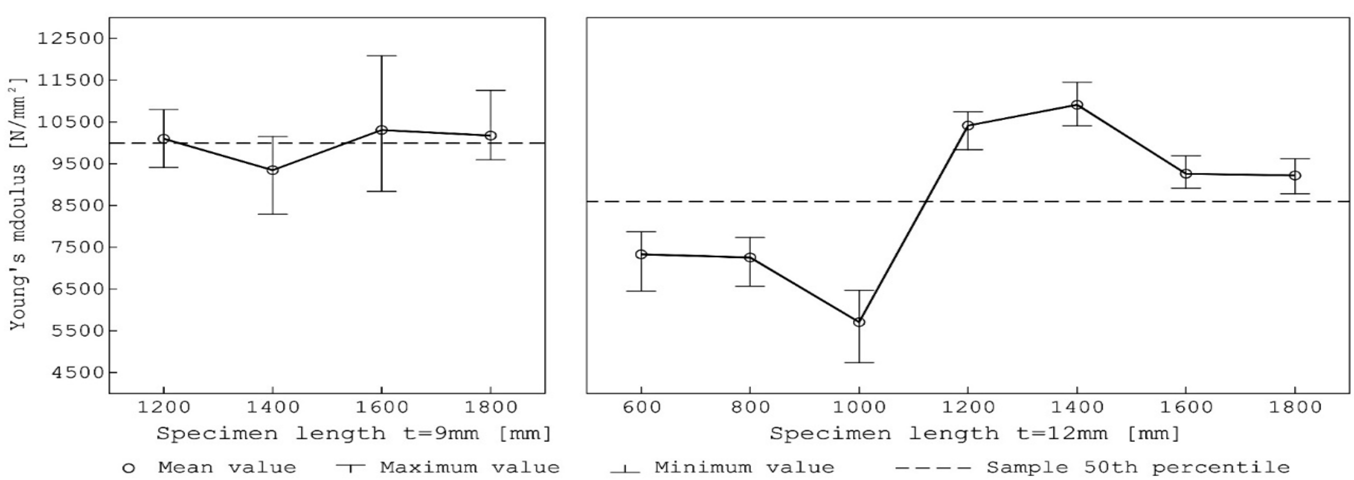

Fig. 11. Modulus of elasticity resulting from compression bending test for 9mm (left) and 12mm (right) thick lauan plywood.

TABLE II
YOUNG'S MODULUS RESULTING FROM COMPRESSION BENDING TEST

Mechanical property	Plywood thickness	Average value resulting from test [N/mm2]	Average value JAS standard [N/mm2]
Elastic modulus *Em,0*	9mm	9982	6500
	12mm	8586	5500

TABLE III
BENDING STRENGTH RESULTING FROM COMPRESSION BENDING TEST

Mechanical property	Plywood thickness	Characteristic value resulting from test [N/mm2]	Characteristic value JAS standard [N/mm2]
Bending strength fm,0,k	9mm	35.52	28.00
	12mm	35.80	24.00

For statistical analysis of bending strength results, the coefficient of variation of the sample of each plywood thickness has been calculated and compared, again, with average value from 'Wood Handbook' -Forest Product Laboratory of Madison, 1999- details for strength in bending tests, 16%. 12mm thick plywood sample obtained a coefficient of variation of 13.8%, so no modification is needed. However, the coefficient of variation obtained for the original 9mm plywood sample is 23.0%, so specimens that deviate the most from the average are disregarded. After eliminating the upper and lower extreme cases, coefficient of variation is recalculated and the result is 15.7%, so corrected sample is considered valid, and 5% and 50% percentiles are computed.

Fig. 12. shows that, for both thicknesses, maximum strength values are obtained when specimen length is in the range 1200-1400mm and that appreciably lower values are obtained if slenderness is reduced. Something similar occurred -not so clearly for 9mm plywood, but for 12mm thickness- in elastic modulus plots. A possible explanation for the reduction of strength and stiffness values for lower slendernesses can be found in the increase of shear effects. Not surprisingly, standards used for plywood characterization by means of bending tests fix specimen slenderness. However, there is no unanimity on the appropriate ratio for the 4-point bending test: in the American standard, ASTM D3043, plywood length/thickness ratio in longitudinal direction is 48; in the UNE-EN 789 standard, the specimen must have a length equal to 57 times the thickness (ratio calculated for a thickness of 12mm); and in the 4 point bending JAS standard, span should be 45 times the thickness. Although the influence of shear is lower in compression bending test, it is not possible to eliminate the deflection component caused by shear. However, results of the tests carried out for this research work, show a tendency towards homogenization of the values for mechanical properties when slenderness is greater than 100.

Strength value resulting from compression bending tests is higher than that established by JAS standard (Table 3), as expected. As mentioned before, the 9mm thick plywood sample was corrected by eliminating the specimens with the highest and lowest strength values, since the specimen with the smallest value deviated greatly from the average. In the original sample tested, strength characteristic value was conditioned by the unique two specimens with brittle failure on tensile face (specimens designated as 9_1600_3 and 9_1800_2). This failure mode was caused by the presence of a knot in the tensile face that affected the entire width of specimen. Under normal conditions of use of plywood slats, the widths will be larger, and the probability that the knot will affect to the entire width of the structural element will be smaller, reducing its influence on the strenght. Therefore, in addition to statistical logic, the specimen correction operation is consistent with the expected behavior of the material within the structural system.

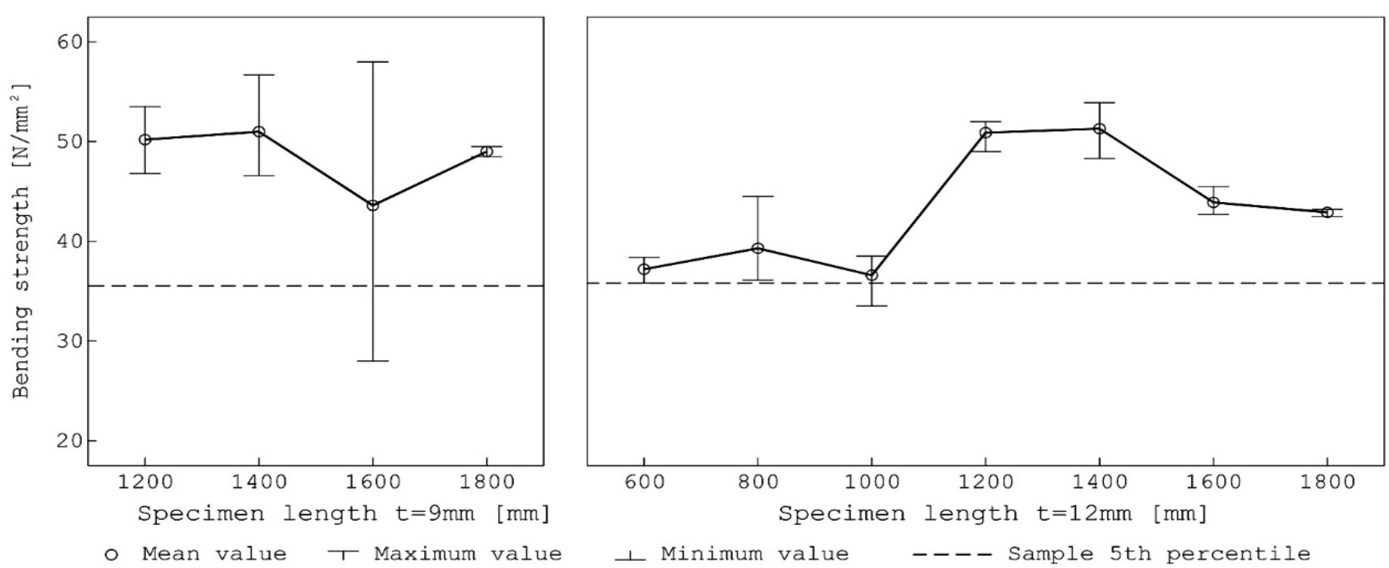

Fig. 12. Strength resulting from compression bending test for 9mm (left) and 12mm (right) thick lauan plywood.

Since the method for achieving bending is not through the application of a force perpendicular to the element, but through the destabilization produced by buckling, the summand that computes the effects of external force on compressive stresses has been considered in strength calculation. However, the significance of these compression stresses decreases as slenderness increases. This is evident if the characteristics of the test are extreme: for very low slenderness, of the order of 1, specimen does not buckle, and the test is a simple compression test where bending stresses do not exist and only compressive stresses appear. As slenderness increases, buckling appears and compressive stresses lose importance while those due to eccentricity increase. For lengths equal to 50 times the thickness (Figure 13), compressive stresses reach only 3% of the total, and the value fall until 1% when slenderness is over 100.

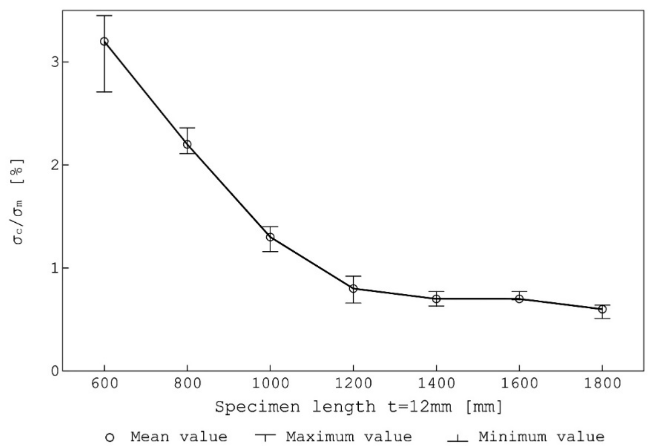

Fig. 13. Relationship between compressive stress and total stress at failure as a function of the slenderness of 12mm thick plywood specimen.

As a final consideration, it is worth adding an energetic interpretation of the results of compression bending test. The load-displacement typical diagram of the experiment labelled as Fig. 2 shows how, once the value of maximum load is reached, the force produced by the hydraulic piston decreases considerably. To measure deformation during the buckling process, control over the experiment was defined by successively increasing the displacement of one end of the slat. If load increase had been used, the buckling of the bar would have been explosive and would not have allowed the measurements to be made. This fact has an energetic reading. As the free end is displaced, compression strain energy increases. Until the moment when compressive and bending strain energy equalize. At that precise moment, the system changes its shape to a lower energy one. This tendency to lower energy shapes is the reason why the use of compression prestressing as a method to lighten structural systems tends to be avoided. An external loading hypothesis that means an increase in initial stresses may lead to local instabilities that trigger global structural collapse. So, snap-through processes must be checked out to guarantee stability.

IV. Conclusions

From methodological point of view, compression bending test has been shown to be a valid procedure for the characterization of linear or planar construction materials with large slenderness, since it was found that the relationship between the elastic moduli of the curves of tensioned and compressed faces is equal to those obtained in the corresponding specific tests. Optimal specimen length/thickness ratio is over 100, when simultaneously, compressive stress component is under 1% of total stress and strength and young's modulus results are more homogenous. Increasing slenderness range reduce shear force effects so correspondent strength values are the highest of the sample.

Despite the careful treatment taken in the preparation of the experiments, originally unexpected interactions revealed that compression bending test is very sensitive to initial instability: curvature of the specimen and initial eccentricity of the load. These factors affect results because they generate alternative elastica in pre-buckling state of specimen. Their influence depends on the order of magnitude of the alterations, being especially decisive when their value is very small but not negligible. However, if the initial curvature or the eccentricity in the application of the load is greater than the thickness of the specimen, their negative effects are eliminated, and the test results obtained correspond to what is expected.

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