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RESEARCH PAPER

Experimental determination of the limiting flexibility of eucalyptus wood
for axially compressed elementsDavid Cajamarca-Zuniga^{1,2*}, Cristhian Carrasco¹, Belen Molina¹¹Catholic University of Cuenca, Av. De las Americas & Humboldt, Cuenca, 010101, Republic of Ecuador²Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation

*cajamarca.zuniga@gmail.com

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Abstract

Relevance. Wood is one of the most widely used building materials throughout history, and because of its physical-mechanical properties it mainly has been used in flexed and compressed elements. Eucalyptus was introduced to Latin America in the mid-19th century and nowadays is one of the most used woods for construction in the Andean region of Ecuador. To designing slender structural elements under axial loading engineers usually use the Euler formula, but it is applicable only if the compression stress does not exceed the proportional limit. One way to determine if the compression stress will be below the proportional limit is by comparing of the slenderness of the element with the limiting flexibility of its material which allows knowing if the buckling will occur in the elastic zone where Euler formula applies. **The aim of the work** – determine the magnitude of the limiting flexibility of eucalyptus, since this wood has been the subject of some investigations, however, no information about the limiting flexibility magnitude for the calculation of axially compressed elements. **Methods.** The laboratory tests to determine the magnitudes of the modulus of elasticity, proportional limit, admissible compression stress and limiting flexibility was carried out. Results. This experimental investigation shows that the magnitude of the limiting flexibility or so-called critical slenderness ratio for eucalyptus globulus is 59.

Keywords: axial loading, central-compressed elements, critical force, critical slenderness ratio, eucalyptus, limiting flexibility, proportionality stress

For citation

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Introduction

Eucalyptus is a fast growing diffuse-porous hardwood genus of trees from the Myrtle family [1], there are about 500 species in the world, most of which are

originally from Australia. The genus eucalyptus first was described by the French botanist C.L. L'Héritier in 1788 [2]. After the introduction of the eucalyptus to Ecuador, a large variety of forests of this tree appeared in highlands where the spice eucalyptus globulus dominates among others [3]. The Eucalyptus is a widely used wood in the construction sector in the Andean region of Ecuador [4], it can reach an height of 20 m and a diameter of 0.25 m at the age of 5 to 10 years, while at an older age it can reach a height of 60 m.

This investigation aims to determine the magnitude of the flexibility of Eucalyptus since this wood has not been the subject of investigations like other woods [5] and the existing investigations about it [5–11] don't

David Cajamarca-Zuniga, Master of Science, PhD postgraduate student, Department of Civil Engineering, Engineering Academy of RUDN University; Docent of the Department of Civil Engineering at CUC; ORCID iD: <https://orcid.org/0000-0001-8796-4635>, eLIBRARY SPIN-code: 6178-4383.

Cristhian Carrasco, Civil Engineer graduate, Department of Civil Engineering; ORCID iD: <https://orcid.org/0000-0002-3019-5721>.

Belen Molina, Civil Engineer graduate, Department of Civil Engineering; ORCID iD: <https://orcid.org/0000-0002-0001-2154>.

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give information about the limiting flexibility (critical slenderness ratio) for the calculation of axially compressed elements.

In this article are presented the results of laboratory tests on the definition of the magnitude of admissible compressive stress parallel to grain, modulus of elasticity and proportional stress with the purpose of the definition of the value of limiting flexibility (λ_{lim}) of this material.

For the calculation of axially compressed elements, the magnitude of the critical force usually is determined with the Euler formula, however, it is applicable only when the axial compression stresses do not exceed the stress of proportionality. Therefore, is necessary to determine if the compression stresses will be below the proportional range, by comparing the magnitude of the slenderness λ (geometric characteristic of the element) with the magnitude of the limiting-flexibility λ_{lim} (mechanical characteristic of the material), this comparison allows to determine if the element has great or intermediate slenderness, to proceed to the calculation of the element considering the risk of loss of stability (buckling).

If the element has great slenderness, the buckling would occur in the elastic zone and Euler formula can be applied to determine the magnitude of the critical load, but if the element has “intermediate” slenderness the loss of stability would occur in the plastic zone and the Euler formula is no more applicable, here empirical formulas such as F.S. Yasinskiy (1895) [12] could be used, however, the problem is determining if the element has “great” or “intermediate” slenderness, and the answer to this question is in the magnitude of limiting flexibility.

1. Methodology

First, a bending test was performed to verify the obtained results by comparing them with the information available about the bending mechanical properties of eucalyptus, then the compression test was performed on 21 various-sizes samples to analyse their behaviour according to the variation of slenderness. The experimental analysis was based on norms and standards of the “Pan American Standards Commission” (COPANT 461, COPANT 464, COPANT 555), “American Society for Testing and Materials” ASTM D143-94 (2000) and “International Organization for Standardization” ISO 13061-17:2017 [13–17], which describe the materials, equipment and procedures to obtain: the stresses for ultimate bending and compression parallel to the grain, the average modulus of elasticity, the maximum breaking load and the stress-strain graph, that permit determine the mechanical properties of the wood.



Figure 1. Compression test

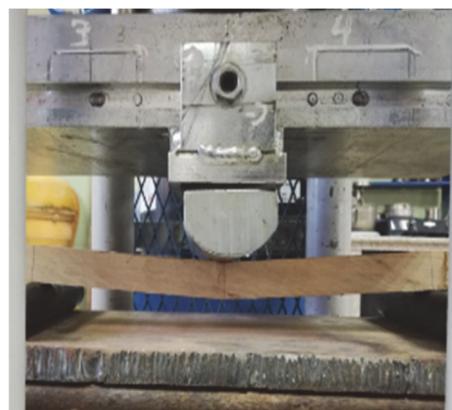


Figure 2. Flexure test

The compression test (Figure 1) was carried out according to standards in samples with a cross-section of 5×5 cm and 20 cm of length [14], the flexure test (Figure 2) was carried out in samples with a cross section of 5×5 cm and 75 cm between supports, however an alternative cross-section of 2×2×30 cm could be used for samples from trees of small diameter (30 cm or less) and also when long samples cannot be obtained due to a bent tree, tilting of grains, knots or other defects [15].

2. Bending test

The flexural testing was carried out on 20 samples, in accordance with [13; 15–17], the information about deflections and loads were recorded, and then the corresponding magnitude of bending moment and normal stress under flexure were calculated in order to obtain the stress-strain curve and the modulus of elasticity.

The results of the flexure test are shown in the Figure 3. According to the results of this experiment, the modulus of elasticity in bending for the eucalyptus

globulus is $E = 104\,180.68\text{ kgf/cm}^2$, the ultimate strength is 800.46 kgf/cm^2 , and the proportional limit is 517.47 kgf/cm^2 .

Table 1

Flexural mechanical properties

Flexural mechanical properties of eucalyptus globulus		
	kgf/cm ²	mPa
Modulus of elasticity	104 180.68	10 220.12
Stress of the proportional limit	517.47	50.76
Ultimate strength	800.46	78.53

The obtained results are according with the existing information about the flexure mechanical properties of eucalyptus, some of which is shown in [1; 6–9; 18–21].

3. Compression parallel to the grain test

The experiments were performed on 21 specimens based on the standards [14; 16; 17], taking into account that the COPANT-464 standard specifies that the cross-section of the specimen for the compression test parallel to the grain is $5 \times 5 \times 20\text{ cm}$ [14]. The standard dimensions, both in height and in the cross-section, were varied to test different slendernesses. The dimensions of the analysed samples have shown in Table 2.

The compression test was performed until the failure of each sample, and both the longitudinal deformation and the corresponding compression load were registered to calculate the compression stresses according to the cross-sections of each sample and to get the stress-strain curves (Figure 4).

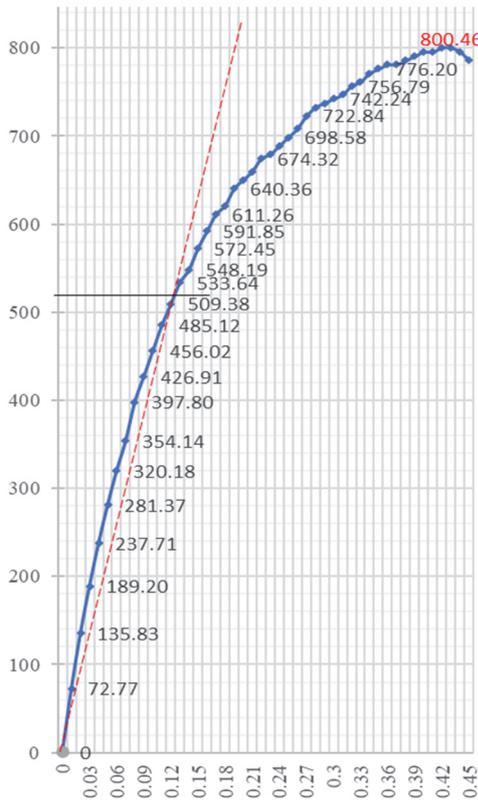


Figure 3. Stress-strain curve for bending, kgf/cm²

Table 2

Dimensions of specimens for compression test

ID.Nº.	Length, cm	a_{max} , cm	a_{min} , cm	Mass, kg	Area, cm ²	I_{min} , cm ⁴	i_{min} , cm	λ	Specific weight, kgf/m ³
1	13-c	4.10	4.10	0.070	15.990	20.267	1.13	3.64	1067.74
2	13-a	5.15	4.10	0.080	15.990	20.267	1.13	4.57	971.48
3	13-b	6.60	4.10	0.100	15.990	20.267	1.13	5.86	947.56
4	8	9.59	3.95	0.160	15.603	20.287	1.14	8.41	1069.32
5	20	10.07	2.95	0.090	8.614	6.121	0.84	11.95	1037.55
6	19	10.16	2.93	0.090	8.585	6.142	0.85	12.01	1031.84
7	9	10.20	3.99	0.170	15.800	20.648	1.14	8.92	1054.83
8	18	10.20	2.14	0.060	4.408	1.559	0.59	17.15	1334.35
9	7	12.30	3.91	0.220	15.210	19.180	1.12	10.95	1175.96
10	5	14.57	4.00	0.230	15.720	20.233	1.13	12.84	1004.19
11	4	15.10	3.93	0.240	13.834	14.284	1.02	14.86	1148.94
12	1	15.14	3.97	0.240	15.761	20.700	1.15	13.21	1005.78
13	2	15.26	4.00	0.240	15.640	19.925	1.13	13.52	1005.59
14	3	15.30	3.90	0.230	14.703	17.414	1.09	14.06	1022.42
15	17	19.45	3.99	0.340	15.761	20.492	1.14	17.06	1109.15
16	10	19.75	3.97	0.430	15.721	20.544	1.14	17.28	1384.89
17	12	19.90	3.98	0.390	15.761	20.596	1.14	17.41	1243.46
18	14	19.90	4.04	0.380	15.877	20.435	1.13	17.54	1202.70
19	16	19.98	3.90	0.320	13.455	13.346	1.00	20.06	1190.34
20	21	20.05	2.95	0.180	8.555	5.996	0.84	23.95	1049.39
21	15	20.10	4.04	0.350	15.837	20.280	1.13	17.76	1099.52

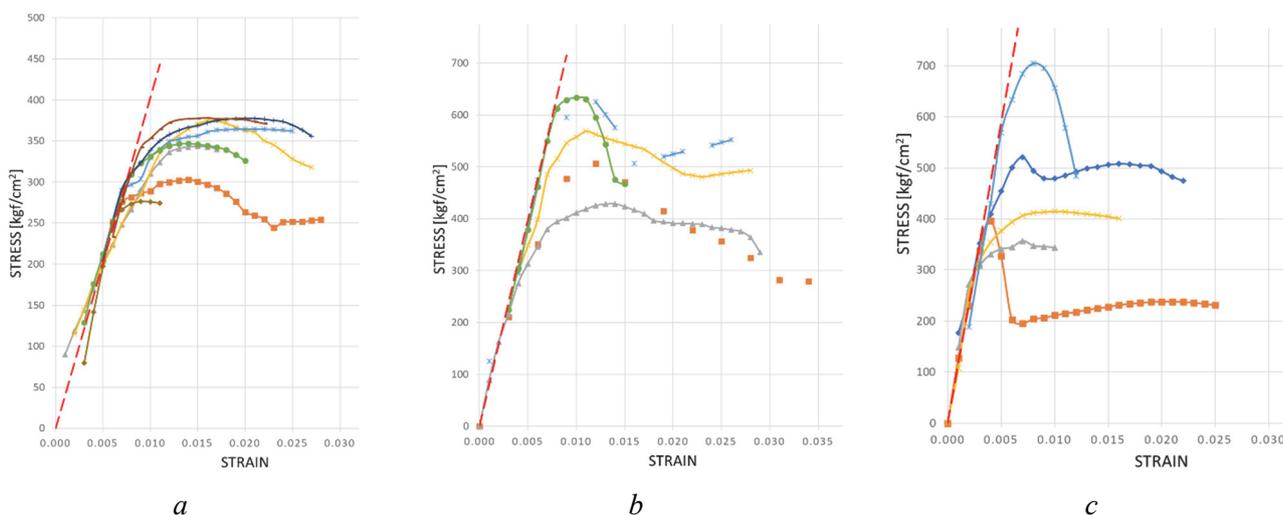


Figure 4. Stress-strain curves for compression parallel to the grain

Compression tests parallel to the grain indicate three characteristic behaviours as a function of the modulus of elasticity. For slenderness less than $\lambda = 20.06$, 42.85% of the samples presented a minimum modulus of elasticity $MOE_{min} = 42\,210.42\text{ kgf/cm}^2$ (Figure 4, a), 33.33% of the samples an intermediate magnitude of $MOE_{int} = 79\,811.58\text{ kgf/cm}^2$ (Figure 4, b) and 23.82% a maximum value of $MOE_{max} = 117\,781.86\text{ kgf/cm}^2$ (Figure 4, c). The results are summarized in the Table 3 and Figure 5.

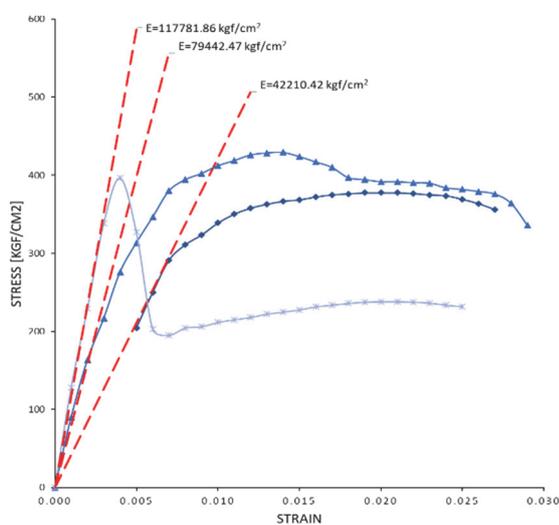


Figure 5. Stress-strain curves and MOE of eucalyptus in compression parallel to the grain

Table 3

Grain-parallel compression mechanical properties

Mechanical properties under compression parallel to the grain		
	Modulus of elasticity, kgf/cm ²	Proportional limit, kgf/cm ²
Minimum (E_{min})	42 210.42	277.61
Intermediate (E_{int})	79 442.47	296.30
Maximum (E_{max})	117 781.86	329.13
Mean value (E_m)	79 811.58	301.01

In this test case, the obtained results are according with the existing information about the compression parallel to the grain mechanical properties of eucalyptus, some of which is shown in [8; 9; 19; 20].

4. Analysis of results

The buckling of a compressed slender-element can lead to a sudden failure of a structure, and as a result, special attention must be given to the design of these elements so they can safely support their intended loadings without buckling. The well-known Euler formula (1) usually is used by engineers to designing slender-structural elements under axial loading, but this formula is applicable only if the compression stress does not exceed the proportional limit.

$$F_{cr} = \frac{\pi^2 \cdot E \cdot I_{min}}{(\mu \cdot L)^2} \tag{1}$$

$$\sigma_{cr} = \frac{F_{cr}}{A} = \frac{\pi^2 \cdot E \cdot I_{min}}{(\mu \cdot L)^2 \cdot A} = \frac{\pi^2 \cdot E \cdot I_{min}}{\mu^2 \cdot L^2 \cdot A} \tag{2}$$

$$i_{min} = \sqrt{\frac{I_{min}}{A}} \tag{3}$$

In the formula (2) the length L , the area moment of inertia I_{min} and area of cross-section A are geometric characteristics of the element, then the expression (2) can be written like this:

$$\sigma_{cr} = \frac{\pi^2 \cdot E \cdot i_{min}^2}{\mu^2 \cdot L^2} \tag{4}$$

In the formula (4) the only geometric characteristics of the element are the radius of gyration i_{min} and the length L , while the effective-length factor is μ . The effective-slenderness ratio of the element as a function of geometric characteristics is shown in the formula (5), in consequence the slenderness can be considered as a geometric characteristic of the element.

$$\lambda = \frac{\mu \cdot L}{i_{\min}} \tag{5}$$

Then, the expression (2) could be wrote like (6).

$$\sigma_{cr} = \frac{\pi^2 \cdot E}{\lambda^2} \leq \sigma_{pl} \tag{6}$$

Here we can see that the critical stress is a function of both a physical-mechanical property of the material E and a geometric characteristic of the element λ , where E represents the constant of proportionality and is applicable under stresses that not exceed the proportional limit, for this reason, Euler formula is applicable only for stresses that do not exceed the proportional limit of the material.

From the expression (6) it is possible to obtain the inequality (7), whose right side represents a physical-mechanical characteristic of the material known as “limiting flexibility” (λ_{lim}).

$$\lambda \geq \pi \cdot \sqrt{\frac{E}{\sigma_{pl}}} = \lambda_{lim} \tag{7}$$

Therefore, if we compare the slenderness of the element with the limiting flexibility of its material and when λ is higher than λ_{lim} , then the buckling will occur in the elastic region and the Euler formula is applicable, otherwise buckling will have a plastic behaviour [22].

We experimentally have determined the physical-mechanical characteristics of eucalyptus, including

the value of the “limiting flexibility”. The results are shown in the Table 4.

Table 4

Experimental results for limiting flexibility of eucalyptus

Mechanical properties of eucalyptus wood under compression parallel to the grain			
	Modulus of elasticity	Proportional limit	Limiting flexibility
	E , kgf/cm ²	σ_{pl} , kgf/cm ²	λ_{lim}
Minimum	42 210.42	277.61	39
Intermediate	79 442.47	296.30	52
Maximum	117 781.86	329.13	59

The Euler formula for “intermediate-slenderness” elements will predict very high values of critical force that do not reflect the failure load seen in practice. To account for this, a correction curve is used for these elements. The J.B. Johnson formula has been shown to correlate well with real buckling failures [23], and is given by the equation (8) [24; 25].

$$\sigma_{cr,J} = \sigma_{adm} - \frac{1}{E} \cdot \left(\frac{\sigma_{adm}}{2\pi} \cdot \lambda \right)^2 \tag{8}$$

Based on the results of the laboratory tests, the stress-slenderness graph (Figure 6) has been prepared, where the Euler and Johnson curves are indicated for the minimum, intermediate, maximum and mean value of the MOE. Consequently, from the graph the magnitude of the limiting flexibility of eucalyptus has been determined as $\lambda_{lim} = 57.5$.

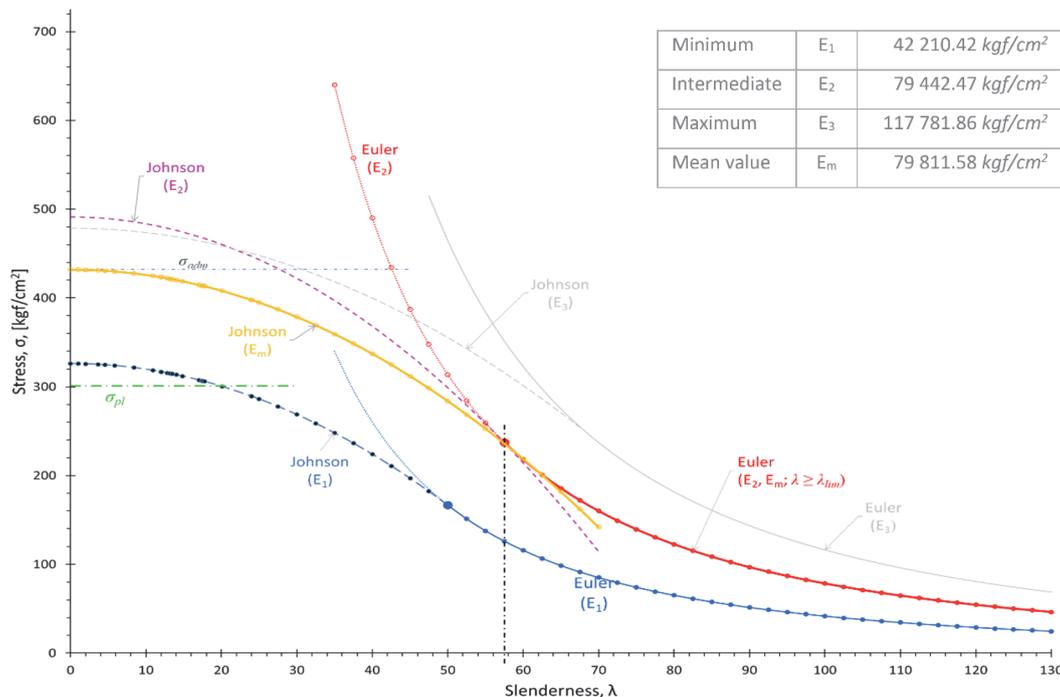


Figure 6. Stress-slenderness graph for eucalyptus wood

Conclusion

According to [10; 11] the mechanical properties (MOE and MOR) of eucalyptus wood under compression parallel to the grain showed a strong correlation with the basic density and the linear and volumetric contractions of the tree.

A total of 41 samples were tested. Based on the tests and the calculations different magnitudes of limiting slenderness have been determined, i.e. from formula (7) we have three values 39, 52 and 59 and 57.5 from the Figure 6 for the average value of the MOE. As we know, the Euler formula for “intermediate-slenderness” elements will predict high-values of critical force. For this reason and safety, we consider that the greater value of limiting slenderness should be assumed. This is 59.

In this experimental investigation, the following mechanical properties of eucalyptus globulus were obtained (Table 5).

Table 5

Mechanical properties of eucalyptus globulus wood

Static bending			
Modulus of elasticity	E	104 180.68	kgf/cm ²
Proportional limit	σ_{pl}	517.47	kgf/cm ²
Ultimate strength	σ_u	800.46	kgf/cm ²
Compression parallel to the grain			
Modulus of elasticity	E	79 811.58	kgf/cm ²
Proportional limit	σ_{pl}	301.01	kgf/cm ²
Admissible stress	σ_{adm}	431.90	kgf/cm ²
Limiting flexibility	λ_{lim}	59	

Although some research has been performed on relevant eucalyptus species, the mechanical behaviour of Eucalyptus wood is far less known compared to other woods [5], e.g. pine or bamboo [22; 26–32].

In this investigation was determined a novel data about the limiting flexibility or so-called “critical slenderness ratio” for eucalyptus globulus, and it could be considered $\lambda_{lim} = 59$. However, there are required more researches about the physical-mechanical properties of the eucalyptus.

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НАУЧНАЯ СТАТЬЯ

Экспериментальное определение предельной гибкости древесины эвкалипта для центрально сжатых элементов

Д. Кахамарка-Сунига^{1,2*}, К. Карраско¹, Б. Молина¹

¹Католический университет г. Куэнка, Республика Эквадор, 010101, Куэнка, Ав. De las Americas & Humboldt

²Российский университет дружбы народов, Российская Федерация, 117198, Москва, ул. Миклухо-Маклая, 6

*cajamarca.zuniga@gmail.com

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Аннотация

Актуальность. Древесина является одним из наиболее широко используемых строительных материалов на протяжении всей истории и, благодаря своим физико-механическим свойствам, в основном применяется в изгибаемых и сжатых элементах. Эвкалипт был завезен в Латинскую Америку в середине XIX в. и в настоящее время является наиболее востребованной древесиной для строительства в Андском регионе Эквадора. Для расчета стержней при осевом сжатии обычно используется формула Эйлера, но она применима, лишь если напряжение сжатия не превышает величины предела пропорциональности. Один из способов определить, находится ли напряжение ниже предела пропорциональности, заключается в сравнении гибкости элемента с предельной гибкостью его материала, что позволяет узнать, будет ли расчет на устойчивость проводиться в упругой зоне, где применима формула Эйлера. **Цель** исследования – определить величину предельной гибкости эвкалипта, так как, хотя эта древесина была предметом нескольких исследований, по-прежнему нет сведений о величине ее предельной гибкости для расчета центрально-сжатых элементов на устойчивость. **Методы.** Проводились лабораторные испытания для установления величины модуля упругости, предела пропорциональности, допустимого напряжения сжатия и предельной гибкости. **Результаты.** Экспериментальное исследование показывает, что величина предельной гибкости для эвкалипта шаровидного равна 59.

Ключевые слова: осевое сжатие, критическая сила, эвкалипт, предельная гибкость, гибкость элемента, предел пропорциональности

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Кахамарка-Сунига Давид, аспирант РУДН; доцент инженерного факультета КУК; eLIBRARY SPIN-код: 6178-4383, ORCID ID: <https://orcid.org/0000-0001-8796-4635>.

Карраско Кристиан, инженер-строитель, выпускник инженерного факультета; ORCID ID: <https://orcid.org/0000-0002-3019-5721>.

Молина Белен, инженер-строитель, выпускница инженерного факультета; ORCID ID: <https://orcid.org/0000-0002-0001-2154>.