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EMBEDMENT STRENGTH OF RECOVERED SPRUCE AND OAK

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ABSTRACT: The circular use of construction materials is an essential step in the drive to reduce the environmental impact of the construction sector. One of the factors that currently limits the ability to reuse timber recovered from demolition in structural applications is the lack of data relating to its structural performance, which would allow for the certification of its characteristics and the development of design guidelines.

This paper presents a study on the embedment performance of recovered timber by determining the embedment strength of spruce and oak specimens recovered from demolition sites in Ireland and Slovenia. Tests were carried out in the parallel and in the perpendicular to the grain directions using three different dowel diameters. The results were comparable with mean values reported in the literature and with the empirical Eurocode 5 predictions. Based on these findings, it can be concluded that the embedment performance of the recovered spruce and oak is equivalent to that of new timber. Further studies on recovered timber of different origin, species, ages and history of use are needed to confirm these findings.

KEYWORDS: Embedment strength, connections, circular construction, recovered timber, spruce, oak

1 INTRODUCTION

More than a third of all waste within the EU comes from construction and demolition [1]. This waste contains valuable natural resources with significant potential for reuse and recycling. In Europe, timber recovered from buildings at the end of life, often referred to as recovered or secondary timber, is, for the most part, converted into chips for use in energy production and, to a lesser extent, for the manufacture of particle boards or pallet blocks [2-4].

Recovered timber is considered to have great reuse potential [5] with maximum environmental benefits achieved through reuse in products with long lifespan, such as those for structural applications in buildings. However, the realisation of this potential is currently inhibited by the lack of grading standards and design guidelines for use of this resource. Recent European projects have begun to address this issue including the Buildings as Material Banks project (BAMB2020) [6], the CaReWood project [7] and the InFutUReWood project [8]. These projects have identified problem areas and proposed technical and methodological solutions to maximise reuse of timber from current buildings especially as a structural material. The most important issue to be addressed is of lack of knowledge of the material properties after the end of its first life.

Some recent studies have applied visual grading and non-destructive testing to characterise the flexural properties of recovered softwoods and hardwoods. Nakajima and Nakagawa [9] developed a visual grading approach for recovered timber boards which acocunts for holes and fissures. Non-destructive evaluation of recovered softwood [10-13] and hardwood [14] timber boards using acoustic methods was used to sort timber for the manufacture of CLT panels, which were subsequently tested in bending.

The issue of connections between recovered wood members has not been addressed to date and the development of design guidelines for such connections will be key to the successful implementation of the circular use of wood in construction.

Dowel-type connections are commonly used to connect structural timber members. For laterally-loaded fasteners, Eurocode 5 (EN1995) [15] provides guidelines derived from the Johansen yield model [16] for the connection capacity. The embedment strength of the timber elements being connected is a required property. For this, the embedment strength may be determined by test or calculation. The embedment strength may be established from experimental tests in accordance with standards, which for Europe is EN 383 [17]. Many studies have reported on embedment strength tests on new timber. Ehlbeck and Werner [18] tested seven different wood

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species (including softwood and hardwoods) using dowel diameters ranging from 8 mm to 30 mm under different load to grain angles. The tests were made in accordance with the then proposed standardised European embedment test method prEN 383 in compression and in tension. The test findings indicated that the embedment strength increases linearly with increasing wood density and that results depend significantly on the fastener diameter. A formula was proposed where the strength is proportional to the timber density with a correction depending on the diameter of the dowel. Sawata and Yasumura [19] tested four grades of Japanese softwood under loading parallel and perpendicular to grain using dowel diameters ranging from 8 mm to 20 mm. The study found that there is significant correlation between embedding strength and density but found that the dowel diameter did not significantly influence results. Sandhaas *et al*. [20][21] compiled a data set of softwood and hardwood embedment tests. Six different wood species with densities ranging from 465 kg/m^3 to over 1200 kg/m^3 were tested, using 12 mm and 24 mm diameter dowels of two different steel grades. All embedment tests were carried out in compression. The influence of the dowel diameter on the embedment strength was found to be of low significance. They presented a simplified formula, discounting any influence of the dowel-to-wood surface area, that gave a more straight-forward design equation to that proposed by Ehlbeck and Werner [18]. Santos et al. [22] found that results of embedment testing to European EN 383 [17] and American ASTM D5764 [23] standards were comparable.

As an alternative to testing, embedment strength may be determined by calculation. Eurocode-5 [15] provides expressions for the embedment strength of new timber, which are a function of the characteristic timber density (the 5th percentile), the dowel diameter, the angle between the load direction and the timber grain, and the timber type. These empirical equations were adapted from those proposed by Ehlbeck and Werner [18] and were derived based on tests on new timber. Their applicability to recovered timber has yet to be established.

This paper presents a study carried out as part of the InFutUReWood project [8] to determine the embedment strength of recovered softwood and hardwood timber. The test programme includes the determination of embedment strength of timber from demolition projects in Ireland and Slovenia. Recovered spruce and oak specimens were tested in compression using dowels of three different diameters in the parallel and perpendicular to the grain directions in accordance with EN 383 [17]**.** Values obtained are compared with published data for new timber and with values from the Eurocode 5 empirical equations [15].

2 MATERIALS AND METHODS

2.1 RECOVERED TIMBER SAMPLES

The three types of recovered timber samples were investigated in the study were: Irish-sourced spruce, Slovenian-sourced spruce, and Slovenian-sourced oak. The Irish-sourced spruce sample was recovered from the roof trusses of a 1970s office block in Dublin, which had been vacant for over two years before its demolition. Grade stamps were visible on some of the boards indicating that the timber was grade TR26 imported spruce. This timber grade is commonly used in Ireland and the UK for roof trusses. TR26 grade timber has characterisitic and mean densities of and 370 kg/m^3 and 444 kg/m^3, respectively [24]. The moisture content of the timber boards at the time of recovery was estimated using a hand-held moisture meter to be between 18% and 23%. This high moisture content was attributed to water ingress onto the structural timber through damaged slates and sarking felt in the roof envelope for a period of time prior to demolition.

The Slovenian spruce was recovered during the refurbishment of the roof of a faculty building at Ljubljana University. The building is estimated to have been built in the years from 1947 to 1949 so the specimens were about 70 years old. The strength grade of the timber is unknown as at that time the JUS (Yugoslavian) norms were not yet in use. During their use in the building the specimens were protected against rain and not insulated. Therefore, they were not exposed to water, but were subjected to varying temperature estimated between -20° C and 50° C. The moisture content estimated with a resistance moisture meter was between 6.5 % and 12.4 %, with an average of 8.9 %. The density of the specimens at moisture equilibrium was between 362 kg/m^3 and 526 kg/m^3, with an average of 426 kg/m^3.

The Slovenian oak sample was recovered during the reconstruction of an external vehicle bridge over the river Sava, which was constructed between 1930 and 1935. During their use on the bridge, the specimens first served as the driving surface, and later they were covered with a new driving surface also made from wood. At first the water and salt from the vehicles would drip onto the specimens directly, and later only partially. The whole time they were exposed to moisture from the surrounding moist air over the river, but they were protected from direct rain by the roof of the bridge. The moisture content of the beams was between 9.1 % and 11.2 % at the time of recovery. The density of the specimens at moisture equilibrium was between 609 kg/m^3 and 860 kg/m^3, with an average of 739 kg/m^3.

Before preparation of the embedment specimens, the timber was conditioned in a chamber with a relative humidity of 65 ± 5% and temperature 20° ± 2° C. The specimens were then cut to the dimensions outlined in EN 383 [17] where the size of the specimen varies with the dowel size used, and with the load direction relative to the wood grain. The cut specimens were returned to the conditioning chamber until testing. The moisture content of all the timber specimens at the time of embedment testing was determined in accordance with EN 13183-1:2002 [25].

2.2 EMBEDMENT TESTING

Specimens for embedment testing were prepared in accordance with EN383 [17] (Figure 1). Smooth high strength steel dowels with diameters of 10 mm, 12 mm and 14 mm were used. A minimum of 10 specimens were tested for each combination of timber source, dowel diameter and loading direction where possible giving a

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total of 191 specimens tested (Table 1). The exception was the 14 mm dowel tests perpendicular to the grain on the Irish-source spruce where only 8 specimens could be manufactured from the available resource. In all, 59 and 65 specimens of Irish-sourced and Slovenian-sourced recovered spruce were tested along with 67 specimens of Slovenian recovered oak.

Each dowel was loaded perpendicular to its axis in accordance with the loading procedure outline in EN 383 [17] and EN 26891 [26]. The dowel deformation was measured using two LDVTs. Tests were terminated when the deformation reached 5 mm or when the specimen failed due to splitting.

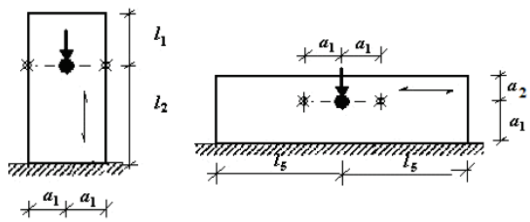

Figure 1: *Test set up for embedment tests parallel to the grain (left) and perpendicular to the grain (right) [2]*

Table 1: *Embedment test series by dowel diameter (dia)*

Series	Dowel dia (mm)	No. Tests Parallel	No. Tests Perpendicular
Spruce Ireland	10	11	10
	12	10	10
	14	10	8
Spruce Slovenia	10	12	11
	12	11	10
	14	10	11
Oak Slovenia	10	12	13
	12	10	10
	14	11	11

3 RESULTS

3.1 LOAD-DISPLACEMENT RESPONSE AND FAILURE MODES

The mean load-displacement responses for tests carried out using 10 mm dowels in the parallel to grain and 14 mm dowels in the perpendicular to grain directions are shown in Figures 2 and 3, respectively. Similar trends were found with other dowels diameters in the respective loaded directions. For all tests, no significant difference was found between the Irish-sourced and Slovenian-sourced spruce. The higher density oak sample was clearly stiffer than the two spruce samples. For the parallel to the grain tests, the peak load was reached before the 5 mm displacement limit specified in EN 383 [17]. This occurred at a displacement of 2 mm for the spruce and 3.5 mm for the oak specimens. As previously reported [21], specimens tested in the parallel to the grain direction are prone to splitting. For the present study, the proportion of specimens failing by splitting reduced with increasing dowel diameter as seen in Table 2. The occurrence of splitting failures occurred for the most part after the peak load had been reached in the tests and therefore does not impact on the embedment strength. This agrees with the findings of Sandhaas *et al*. [21] who found that there was no difference in embedment strength for unreinforced specimens and those reinforced to prevent splitting.

For the perpendicular to the grain tests, the load continued to increase up to the 5 mm displacement limit without reaching a steady state. All of the 94 specimens except one of the 10 mm Slovenian spruce specimens failed in embedment without splitting.

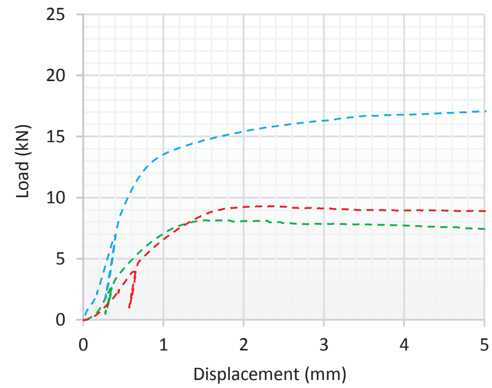

Figure 2: *Embedment test results for 10 mm dowel loaded parallel to the grain (Irish Spruce- green; Slovenian spruce-red; Slovenian oak-blue)*

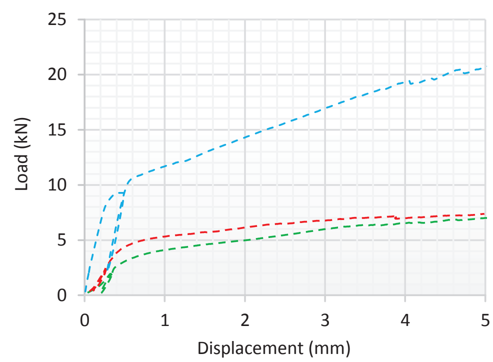

Figure 3: *Embedment test results for 14 mm dowel loaded perpendicular to the grain (Irish Spruce- green; Slovenian spruce-red; Slovenian oak-blue)*

Table 2: *Splitting failures by dowel diameter (dia)*

Series	Dowel dia (mm)	Splitting (%) Parallel	Splitting (%) Perpendicular
Spruce Ireland	10	27	0
	12	10	0
	14	10	0
Spruce Slovenia	10	33	9
	12	18	0
	14	10	0
Oak Slovenia	10	33	0
	12	20	0
	14	18	0

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3.2 EMBEDMENT STRENGTH

The embedment strength for each specimen was determined from the maximum load divided by the area of contact between the dowel and the timber element using Eq. (1).

$$f_h = \frac{F_{max}}{dt} \quad (1)$$

where f_h, in N/mm^2, is the embedment strength, F_{max}, in N, is the maximum load at 5 mm dowel embedment (or failure load due to splitting), d, in mm, denotes the dowel diameter and, t, in mm, represents the thickness of the timber specimen. The mean values of embedment strength and density of the test specimens in each series together with their respective coefficients of variation (COV) are given in Tables 3 and 4 for the parallel to and perpendicular to the grain tests, respectively.

Table 3: *Mean density and embedment strength parallel*

Series	Dowel diameter (mm)	Density kg/m^3 (COV %)	Embedment strength N/mm^2 (COV %)
Spruce Ireland	10	426 (18)	30.2 (30)
	12	408 (6)	26.8 (14)
	14	424 (9)	29.2 (18)
Spruce Slovenia	10	368 (5)	28.7 (10)
	12	374 (12)	27.8 (15)
	14	371 (7)	28.6 (12)
Oak Slovenia	10	628 (9)	55.5 (16)
	12	581 (12)	47.3 (18)
	14	609 (9)	51.5 (14)

Table 4: *Mean density and embedment strength perpendicular*

Series	Dowel diameter (mm)	Density kg/m^3 (COV %)	Embedment strength N/mm^2 (COV %)
Spruce Ireland	10	416 (6)	20.5 (9)
	12	378 (6)	17.4 (23)
	14	399 (8)	16.5 (12)
Spruce Slovenia	10	407 (6)	25.6 (45)
	12	367 (3)	16.4 (13)
	14	393 (8)	17.6 (21)
Oak Slovenia	10	631 (10)	46.2 (29)
	12	653 (10)	50.3 (22)
	14	669 (7)	48.6 (19)

For the parallel to grain direction, the mean embedment strength varied between 26.8 and 30.2 N/mm^2 for the recovered spruce specimens and between 47.3 and 55.5 N/mm^2 for the recovered oak. The COV was 18% or less except for the 10 mm Irish spruce series which was 30%. For the perpendicular to the grain tests, the embedment strength for the recovered spruce specimens varied between 16.4 and 25.6 N/mm^2 while the values for the recovered oak varied from 46.2 to 50.3 N/mm^2. Overall, there was greater variability in the perpendicular to grain results with COV of over 20% in five of the nine series with the largest COV in the 10 mm Slovenian spruce series at 45%.

Boxplots of the embedment strength for the parallel to grain tests by diameter and species are given in Figure 4. There was no significant difference between the embedment properties of the spruce recovered in Ireland and that in Slovenia, regardless the diameter. The higher embedment strength of the oak specimens is likely to be due to their higher density. Similar conclusions can be drawn for the perpendicular to the grain direction.

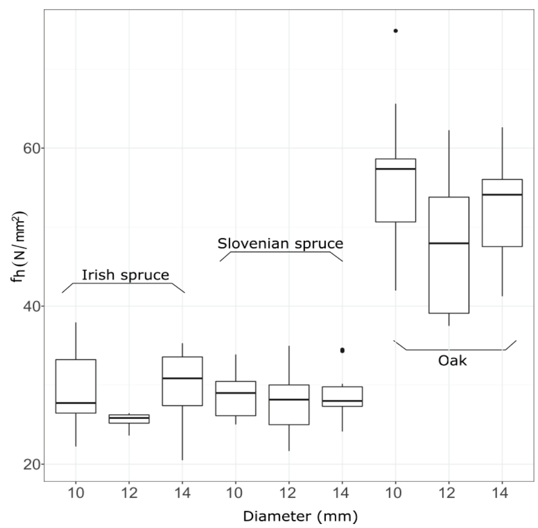

Figure 4: *Box plots of embedment strength parallel to the grain results*

Embedment strength results in the parallel and perpendicular to grain directions were strongly influenced by density as can be seen in Figure 5.

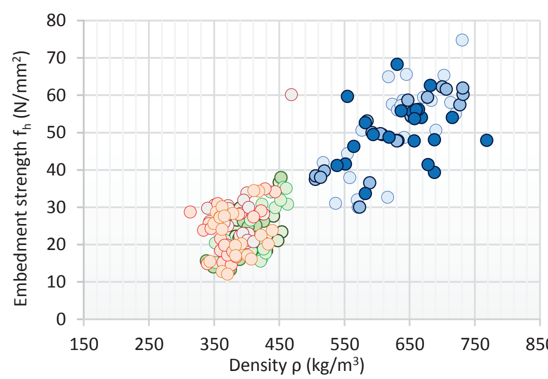

Figure 5: *Embedment strength v density – all specimens (Irish spruce-green; Slovenian spruce –red; Oak – blue)*

For the full dataset of parallel to grain data, the linear relationship between density and embedment strength was very strong (R^2 = 0.90). Including diameter as an additional explanatory variable in the linear regression had a negligible effect on the overall fit of the regression (R^2 = 0.91). The effect of the diameter on the slope and intercept of a linear regression was investigated with ANOVA. The results showed that the diameter affects the intercept ($F_{2\ 94}$ *=3.99, P= 0.02*) but not the slope ($F_{2\ 92}$ *=0.78, P= 0.46*). A multiple comparison at the 95% confidence level showed that 12 mm diameter had an intercept term 3 kN/mm^2 lower than the other two diameters, with no significant differences between the intercept for the 10 mm and 14 mm diameters. It is important to note that these findings are based on the limited dataset in the study and more testing of recovered timber will be needed before any definitive conclusions can be reached.

The overall relationship between density and embedment strength in the perpendicular to grain direction was also very strong ($R^2 = 0.90$). An ANOVA of the softwood data showed that the diameter affects the intercept ($F_{2\ 55} = 9.01$, $P < 0.001$) but not the slope ($F_{2\ 53} = 1.32$, $P = 0.28$). In the softwoods, the 10 mm diameter was about 3 kN/mm^2 higher than those of the 12 mm and 14 mm. The differences between the latter were not statistically significant. For the hardwood, the effect of diameter in the relationship was not significant ($F_{2\ 30} = 1.57$, $P < 0.23$), but the number of tests was roughly half that of the softwoods. Figure 6 shows the relationship of perpendicular to the grain strength by timber type. Even though the effect of the diameter was significant for the embedment strength calculation parallel to the grain and in softwoods tested perpendicular to the grain, trends could not be established. As mentioned earlier, the size of the dataset in the current study does not allow for definitive relationships for the embedment strength of recovered timber to be established. Nevertheless, some trends can be identified.

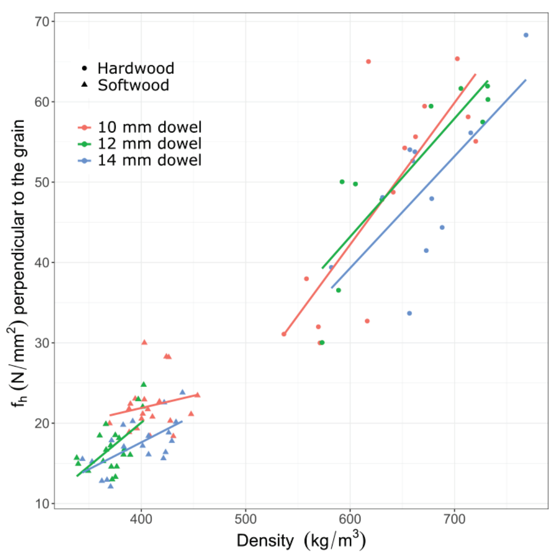

Figure 6: *Relationship between density and embedment strength perpendicular to the grain by dowel diameter*

3.3 COMPARISON WITH PUBLISHED DATA FOR NEW TIMBER AND EC5

The embedment strength values for recovered timber reported here agree reasonably well with values published in the literature from tests on new timber of similar species. Figure 7 shows a comparison of the results for 12 mm dowel parallel to grain tests from the current study compared to data presented by Glišovíc *et al.* [27] and Sandhaas *et al.* [21] for spruce, pine, oak and beech. No impact of aging can be seen in the recovered timber results.

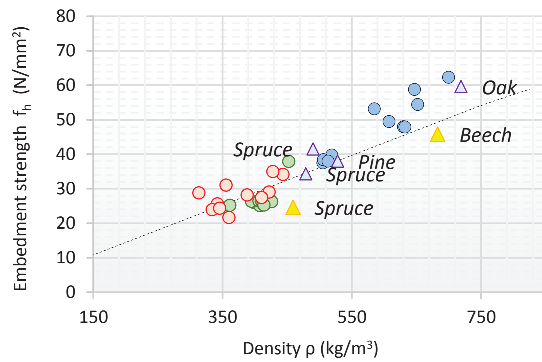

Figure 7: *Embedment strength v density – 12 mm specimens parallel-to-grain (Irish spruce-green; Slovenian spruce – red; oak – blue; Glišovíc et al. [27] – purple; Sandhaas et al. [21] - yellow)*

EC5 [15] provides an empirical equation for embedment strength as a function of density, dowel diameter and angle to grain (Equation (2)).

$$f_{h,\alpha,k} = \frac{0.082\,(1 - 0.01\,d)\rho_k}{k_{90}\,sin^2\alpha\, +\, cos^2\alpha} \qquad (2)$$

where $f_{h,\alpha,k}$, in N/mm^2, represents the characteristic embedment strength, ρ_k, in kg/m^3, denotes the characteristic timber density, d, in mm, represents the dowel diameter, and α, represents the angle of the load to the grain. k_{90}, may be taken as $1.35 + 0.015\,d$ for softwoods, and as $0.90 + 0.015\,d$ for hardwoods. The line representing this equation with the characteristic value replaced by the actual density is shown in Figure 7. For the spruce specimens, the data points are closely aligned with this equation. The equations underpredict the embedment strength of the recovered oak. In general it can be said that the EC5 equation can be used to predict the embedment strength of the recovered timber specimens in the current study. Further work is required to determine its applicability to recovered timber in general.

4 CONCLUSIONS

To support the understanding of the behaviour of recovered timber and support its reuse in new construction, a study was carried out as part of the InFutUReWood project [8] to determine the embedment strength in the parallel and perpendicular to grain directions of recovered spruce and oak. Spruce was recovered during the demolition of roof structures in Ireland and Slovenia and the oak was recovered from the renovation of a vehicle bridge in Slovenia.

Specimens were tested in accordance with EN383 [17] using smooth high strength steel dowels of three different diameters. A total of 191 tests were performed of which 97 were in the parallel to grain direction and 94 perpendicualr to the grain.

For the two spruce series, no significant difference in the embedment strength was found despite the fact that the environmental conditions during the life of the two roof

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structures from which the material was recovered was quite different. For the tests in the parallel to grain direction, the peak load was reached at an embedment of approximately 2mm. A high percentage of specimens failed in splitting before reaching the 5 mm embedment value specified in the standard. For the perpendicular to grain tests, only one specimen failed in splitting.

The embedment strength of the recovered oak specimens was significantly higher that that of the spruce, which is likely due to the higher density. Again, splitting occurred in a high proportion of the parallel to grain tests with no evidence of splitting perpendicular to the grain.

A strong linear relationship was found between embedment strength and density for all tests. The influence of dowel diameter on strength was less clear and will require further testing to establish it.

The results were compared with mean values for new softwood and hardwood timber specimens reported in the literature and were found to be generally in line with these values. The empirical Eurocode 5 predictions for the embedment strength of softwoods and hardwoods were good predictors of the embedment strength of the recovered timber specimens investigated in this study.

Based on these preliminary findings, it can be concluded that the embedment performance of recovered spruce and oak seems to be equivalent to that of new timber. However, further studies on recovered timber of different origin, species, ages and history of use are needed to confirm these findings for recovered timber in general.

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