EVALUATION OF LUMBER FROM DECONSTRUCTED PORTLAND RESIDENTIAL BUILDINGS

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Abstract. Portland, OR, was the first US city to implement a deconstruction ordinance in 2016. Although salvaged lumber from deconstructed dwellings can have high demand, the market for small-sized lumber is near saturation. New applications for this material are required for market development, industry diversification, and the possible expansion of the deconstruction ordinance. Its use in mass timber is an option, but presently no wood property information exists for lumber from deconstructed dwellings, inhibiting its use for structural purposes. Density and dynamic MOE (*E*) of 265, 38 mm × 89 mm (2 × 4) pieces of salvaged Douglas-fir (*Pseudotsuga menziesii*) lumber were determined using a Metriguard Model 340 E-Computer. Additional data collected included sample dimensions, weight, and visual appearance. Over 50% of samples had a calculated stiffness comparable with the highest structural design grade for Coastal Douglas-fir lumber. The presence of knots and damage, present in 66% and 59% of boards, respectively, would likely downgrade boards despite acceptable stiffness. Results show that 96% of samples were sufficiently stiff to meet minimum requirements for the manufacture of E3 grade cross-laminated timber (CLT) panels, and considering defects, this material is suitable for manufacturing CLT. Provision of wood property information for salvaged lumber is critical for market expansion, and this work represents the first characterization of lumber from deconstructed Portland, OR, dwellings.

Keywords: Cross-laminated timber (CLT), deconstruction, density, Douglas-fir, salvaged lumber, stiffness.

INTRODUCTION

The United States generates approximately 70 million tonnes of solid wood waste annually, with municipal solid waste and construction and

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demolition waste being the principal sources. Residues from primary manufacturing facilities represent a sizable proportion but are already heavily used, and excluding what is burnt for heat, already salvaged, or unusable, approximately 29 million tons still have the potential to be recovered (Falk and McKeever 2012). Despite the value that this resource represents, retrieval is uncommon, with the level of recycling for domestic lumber and other structural materials being in the range of 10-11% (Bowyer 2016). The recovery lags well behind the 67.2% recovery rate reported for paper (AF&PA 2017) and that reported for steel (98%) and concrete (82%) (Falk and McKeever 2012) because recovery and reuse is not trivial compared with the aforementioned products unless the intention is to simply burn the biomass.

With a global trend of increasing material consumption (McKeever 2009; Bowyer 2016), it is imperative that society increases efforts to recycle/reuse materials in general, although for lumber specifically, recovery rates of approximately 10% indicate a grossly underutilized resource (Howe et al 2013). As noted by Bowyer (2016), efforts exist to recover a greater proportion of the wood available. Common approaches include increasing deconstruction frequency (rather than demolition), building component reuse, and recovery of discarded wood.

Demolition is effectively the destruction, breakdown, or removal of a structure at the end of its design life (Rahman 2019). It is generally the complete elimination of all building parts, at a specific location and time, for new construction or development (Thomsen et al 2011). Methods used to demolish residential structures typically involve heavy machinery (excavators and bulldozers) which destroy potentially salvageable material, thus preventing reuse (Nunes et al 2019). Conversely, deconstruction is "the process of disassembling a physical structure to its components in reverse order to that used during construction with minimum damage so that they maintain their original physical properties and structural integrity" (Diyamandoglu and Fortuna 2015). It presents a viable alternative to demolition after the reduction in disposal costs (landfill), income generated from the sale of salvaged materials, and potential to create employment are considered (Diyamandoglu and Fortuna 2015; Nunes et al 2019). Recognizing the benefits of deconstruction, the city of Portland, OR, adopted an ordinance in October 2016 which aimed to increase the frequency of building deconstruction (Wood 2016).

In Portland, the number of "single-dwelling structures" that are demolished annually is approximately 300, and of these less than 10% are deconstructed (Wood 2015). Under the existing resolution, "projects seeking a demolition permit for a one- or two-family structure (house or duplex) will be required to fully deconstruct that structure if: 1. The structure was built in 1916 or earlier; or 2. The structure is a designated historic resource" (Wood 2015). Approximately 34% of demolished structures per year in Portland would qualify for these two categories (Wood 2015). Provisions for exemptions will include structures that are determined to pose an immediate safety hazard and structures that are determined to be unsuitable for deconstruction/salvage (eg rot, mold, or fire damaged) (Wood 2015). The Bureau of Planning and Sustainability has provided grants to incentivize involvement in deconstruction projects and also provided training and certification opportunities; to this end, there are now 13 certified deconstruction contractors working in the city. The impacts of the ordinance have been immediate; in a recent status report (dated March 12, 2018), 318 demolition permits for the period October 31, 2016 to October 30, 2017, were approved. Of these, 80 were covered by the deconstruction ordinance (Anderson 2018).

Questions exist regarding the structural quality of lumber salvaged from deconstructed buildings, and few reports exist providing such information. The provision of quality data is critical as without it salvaged wood cannot be used for structural applications. Falk et al (1999a) collected lumber of various sizes from the Twin Cities Army Ammunition Plant in Arden Hills, MN, when it was dismantled in 1995. They focused on engineering properties of 2 × 10 lumber (38 mm × 236 mm). Five hundred pieces were visually graded on-site and indicated that 28.4% of the 500 pieces were Select Structural, 8.4% No. 1, 19.4% No. 2, 15.6% No. 3, and 28.2% economy (<No. 3), but it was estimated that up to 30% of the lumber was downgraded as a result of damage (mainly splits) during deconstruction. A subsample of 100 randomly selected pieces were shipped to the USDA Forest Service Forest Products Laboratory (Madison, WI) and destructively tested. Measured stiffness was similar to that of lumber produced commercially at the time of the publication; however, lumber strength was less than expected. It was thought that chemical contamination related to the use of the building (production of magazines for explosives) may have weakened the lumber; however, chemical analysis of wood from the building was inconclusive. An interesting finding was the species used in construction because it was believed that Douglas-fir (*Pseudotsuga menziesii*) was used. An examination by a wood anatomist revealed that 53% was Douglas-fir, 25% Hemlock-Fir, and 22% southern pine. In a related study of lumber from the Fort Ord US Army Military Reservation in Marina, CA, it was again observed that damage affected the grade assigned in over one-third of the lumber (Falk et al 1999b). Careful deconstruction practices were emphasized to increase the yield of high grades of lumber.

It can be deduced from the age of the buildings being deconstructed in Portland that the lumber was cut from "old-growth" trees and has the potential to be of exceptional quality; however, no reports exist that characterize the wood from this important resource. Therefore, this study aimed to characterize wood sourced from deconstructed buildings in the Portland metro area in hopes of supporting market development, industry diversification, and the possible expansion of the deconstruction ordinance. The research is part of a larger study examining the utilization of reclaimed dimension lumber for the manufacture of cross-laminated timber (CLT) panels. The study was motivated by the need to find new high-value markets for salvaged lumber as concerns exist that supply of dimensional lumber now available owing to the deconstruction ordinance exceeds what the market can absorb (Anderson 2018).

MATERIAL AND METHODS

Salvaged Lumber

A total of 483 rough-cut 38 mm × 89 mm (2 × 4) pieces of salvaged lumber (892.31 linear meter total length) were supplied by three deconstruction contractors in the Portland metro area. Contractors were asked to provide material that had minimal metal, paint, and no hazardous contaminants. Rough-cut lumber was selected because it represents lumber typical of what is being salvaged from dwellings in Portland built before 1916. Lumber were separated by length as the target CLT panel size was 1.14 m × 2.28 m. Two groups were identified: <2.3 m for use in the minor direction of CLT panels and ≥ 2.3 m for the major direction. There were 267 boards in the <2.3 m group and 216 boards in the ≥ 2.3 m group. In addition to length, sample width and thickness were also measured.

Lumber Assessment

A Metriguard Model 340 E-Computer (Metriguard Inc., Pullman, WA) was used to grade the lumber for wood stiffness measurements. Grading was attempted on all 483 boards; however, 218 boards were too short to be graded. The Metriguard Model 340 E-Computer is a portable test system for calculating the dynamic MOE (E) of a board by measuring its natural frequency (Hz) induced by tapping the center of the board with a small rubber mallet in the center of the span. It consists of two tripods, one with a calibrated load-cell and the other with a knife-edge, and an interface unit. Samples were placed flatwise on the knife and load cell, with a 25-mm overhang on each side. Weight and five frequency measurements were collected for each board. The average frequency was determined and used to calculate an E-value for each tested board. If the five readings were not recorded after 10 taps (when the board was too short to record a vibration frequency), the sample was set aside and testing continued. Data recorded for each sample (dimensions, weight, and average frequency) were used to calculate E, in pounds per square inch (psi), according to (Metriguard 2011):

$$E = \left(f_n^2 \cdot W \cdot L^3\right) / \left(K \cdot b \cdot h^3\right), \quad (1)$$

where E is the MOE (psi), f_n is the undamped natural frequency (Hz), W is the sample weight in pounds, L is the span length in inches (total length minus two inches of overhang), K is the adjustment of constant used to accommodate the units used and the support conditions (equal to 79.37), b is the width of the test sample in inches (horizontal distance), and h is the thickness of the test sample in inches (vertical distance).

When the samples were tested by the Metriguard, notes were also taken on visual appearance including splits/checks, knots, biodegradation, surface damage, holes, wane, pitch/resin pockets, warp, and uneven surface. Defects were either marked as present or absent. Brief descriptions of identified defects are as follows:

1. Splits and/or checks: appeared to be natural cracks formed by wood shrink/swelling, or cracks possibly formed during deconstruction and material handling
2. Knots: any type of knot
3. Biodegradation: evidence of any rot and/or insect attack
4. Holes: only holes arising from wiring and construction
5. Wane: included any bark, or tree exterior present on boards
6. Pitch and/or resin pockets: the presence of surface resin or resin-filled cavities
7. Warp: twisted or distorted boards
8. Uneven surface: boards with a face that was milled unevenly

Mold, nail holes, and other small defects were disregarded when visually inspecting the lumber.

Thirty MC readings were randomly collected from the graded salvaged lumber. Average MC was then calculated and used to adjust E to 15% MC using the following formula (ASTM 2007):

$$S_2 = S_1 \cdot (B_1 - (B_2 \cdot M_2)) / (B_1 - (B_2 \cdot M_1)), \quad (2)$$

where S_2 is the adjusted E to 15% MC, S_1 is the calculated elasticity (psi) at the average MC, B_1 is a constant (equal to 1.857), B_2 is a constant (equal to 0.0237), M_1 is the average MC (%) when tested, and M_2 is the target MC of 15%. After grading boards and correcting for MC, E values were converted from psi to gigapascals (GPa).

RESULTS AND DISCUSSION

Dimensional measurements and density were recorded for all 483 rough-cut pieces of salvaged lumber. A total of 265 boards (all 216 boards in the $\geq$2.3 m group and 49 of the 267 boards in the <2.3 m group) were graded using the Metriguard system, and subsequently, visually inspected for defects. A summary of the groups, attempts at grading, and salvaged boards graded are shown in Table 1.

Visual Examination

Examination of the end-grain (or cross-sectional surface) of the reclaimed lumber indicated that it was of high quality and consistent with lumber sourced from old-growth forests (Fig 1). Many pieces were quarter sawn, had ring boundaries that were close to linear, and had exceptionally tight growth rings; all these indicate that the lumber was milled from very old, slow-growing trees. The average ring count per centimeter of these boards was eight rings and ranged from 2 to 19 rings. Of these 48 randomly selected boards, 17 had 10 or more rings per centimeter. Wood

Table 1. Summary of salvaged lumber groups and grading using the Metriguard system.

Group (m)	No. of boards	Attempted	Graded	Not graded
<2.3	267	267	49	218
≥2.3	216	216	216	0
Total	483	483	265	218

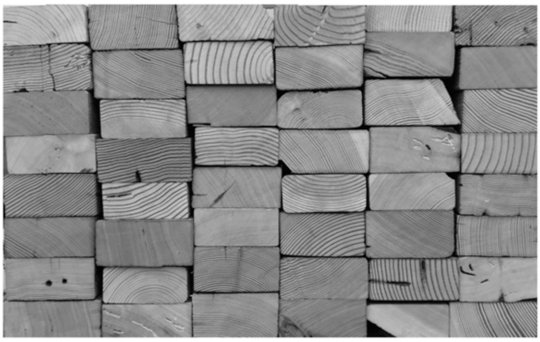

Figure 1. Picture of end-grain for a random sample of salvaged lumber.

species identification was also performed on these boards using hand lens, and all were Douglas-fir. As a consequence, all salvaged lumber in this study were compared with published characteristics, standards, and test values for Douglas-fir.

A summary of the visual defects observed, for the 265 graded samples, is provided in Table 2. Knots were the most common defect observed occurring in 66% of samples. For some pieces of lumber, the knot size was extreme, covering over 75% of wide-face width and containing large cracks. Knots of this magnitude are rare to find in today's commercial structural lumber because modern silvicultural practices focus on straight, clear wood through self-pruning (due to high planting density and competition), genetic selection (for branch quantity, size, and angle), and short rotation-age (restricts the size/age a branch can reach). Checks and/or splits, damage, and holes were also common with 59% of all samples, showing some sign of physical degradation. No samples showed signs of warp.

Table 2. List of defects identified and their relative abundance (265 samples).

Visual defect	Tested (%)
No major defects	9
Checks/splits	34
Knots	66
Biodegradation	5
Damage	28
Holes	11
Wane	7
Pitch	11
Warp	0
Uneven surface	3

Evidence of resin and biodegradation were found in 11% and 5% of all samples, respectively. In a living tree, resin has a protective role, repelling insects and fungi, and covering wounds, eg from physical damage or fire. For Douglas-fir, resin "bleed" over time is common on non–kiln-dried pieces and can either appear as dark spots on the ends of fresh-cut lumber or beads of resin on the surface. Resin pockets were less frequent but are a common feature in Douglas-fir and arise from damage caused by the Douglas-fir beetle (*Dendroctonus pseudotsugae*) (Belluschi et al 1965). Agents of biodegradation were wood-decay fungi and insects. The two wood-decay fungi found were likely brown trunk rot and red ring rot (sometimes called white spec) (Hollingsworth 2018). Although brown trunk rot (*Laricifomes officinalis*) is a common problem in Douglas-fir, producing decay that appears dark brown with a checked surface, the one sample found with this decay only showed minimal damage. Red ring rot (*Porodaedalea pini*) occurred in seven samples and is also common in older Douglas-fir. Damage observed from red ring rot appeared moderate to advanced with a honeycomb appearance and white, spindle-shaped pockets of decay (Hollingsworth 2018).

Four boards showed evidence of insect attack consistent with Cerambycidae and ambrosia beetles. Cerambycidae are long-horned beetles and round-headed wood borers. Species in this family that reside in the Pacific Northwest generally infect only standing timber or green lumber, leaving large tunnels that can extend the length of boards. Ambrosia wood-boring beetles (Scolytinae subfamily) make much smaller tunnels than Cerambycidae. Ambrosia beetles get their name from the symbiotic relationship they have with the "ambrosia fungus." Ambrosia fungus is a mold/stain fungus, ie usually beetle-specific, originating from small holes located on the exoskeleton of beetles. In exchange for habitat, transportation, and food, beetles and larvae use this fungus as nourishment because they do not consume wood directly (Six 2003). When the beetle and fungus find a host, beetle tunnels are typically lined with black stain and/or contain distinctive black rings owing to the symbiotic fungal relationship; however, they were observed for only one board. Interestingly, this board also showed other beetle attack, brown trunk rot, physical damage, and resin; however, it is sufficiently stiff for use in CLT.

The cross-sectional dimensions of the lumber were quite variable (Fig 1). Since 1924, the American Lumber Standard Committee have developed voluntary product standards published under procedures established by the US Department of Commerce. In the early 1970s, publishing of Voluntary Product Standard PS 20 and development of the first National Grading Rule for Softwood Dimensional Lumber resulted in uniform lumber sizes, grade names, and grading provisions. The standard size for finished dry nominal 2 × 4 lumber, ie currently milled and distributed, is 38.0 mm × 89.0 mm. Permitted variation in lumber dimension is less than 0.79 mm in 20% of pieces and more than 0.79 mm in all pieces for No. 2 and better grades, and more than 1.59 mm on opposing faces in 20% of the pieces for Studs, Utility, and No. 3 grades (WWPA 1991).

Nondestructive Testing

Salvaged lumber dimensions and density. As boards used in this study were acquired from houses older than the first established grading rules, uniform dimensions were not expected. Both average thickness and width of all 483 boards were greater than current grading standards for 2 × 4 lumber: 43.0 mm and 90.6 mm, respectively (Table 3). Differences between the largest and smallest measurement for thickness and width were 15.8 mm and 16.3 mm, respectively (Fig 2). Like standard lumber sizes, the differences in dimensions among boards also exceeded the permitted variation in lumber described by the current grading rules.

Taking note of the width and thickness variations in salvaged lumber is important because, compared with lumber presently cut, this will be an issue for CLT manufacturers. All lumber would need to be planed to a consistent thickness and be within tolerances, before gluing for meeting performance standards. Thickness consistency is required for manufacturing, but processing to achieve consistent width may also be required; however, it is not absolutely necessary and may depend on the manufacturer. The desired end product may also be important. Glulam, eg manufactured under the CaReWood process described in Risse et al (2017), would require lamellae cross-sectional dimensions to be carefully controlled.

Douglas-fir is native to the Pacific Northwest of the United States and Canada and has been the most common softwood species used for construction in the Portland area because of its strength, durability, and workability. The reported average density for this species is 510 kg/m^3 (Kretschmann 2010). The density of all 483 boards (Fig 3) was calculated using measured dimensions and the weight provided by the Metriguard. Although the coefficient of variation for density was higher than that of thickness and width, 11% as opposed to 6% and 3%, respectively, the average density of 530.7 kg/m^3 is comparable with published values (Table 3).

Grading. Samples were compared with design standards only after adjusting to 15% MC (as required). The average MC for the 30 random

Table 3. Salvaged lumber summary statistics (483 samples).

	Average	Maximum	Minimum	SD	CoV (%)
Thickness (mm)	43.02	51.56	35.81	2.71	6
Width (mm)	90.55	100.58	84.33	2.38	3
Density (kg/m^3)	530.70	718.41	338.13	59.96	11

CoV, coefficient of variation.

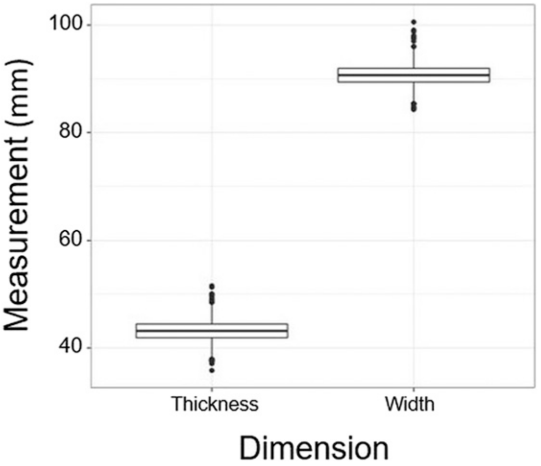

Figure 2. Thickness and width distributions (mm) for 483 pieces of salvaged lumber.

measurements equaled 11% (SD = 2%) and was used for MC adjustment. Of the 265 samples that could be graded using the Metriguard, 72% had an *E*-value of 11 GPa or greater, the design value for No. 2 Douglas-Fir–larch. Disregarding visual defects, Table 4 shows the percentage of boards in each visual grading category based on National Design Standards stiffness values (AWC 2015). Because the samples tested are part of a larger study, *E*-values were also compared with the allowable stress design reference values for laminations used in manufacturing CLT (ANSI/APA 2018). The larger study aimed for the CLT layup grade of E3, which required laminations in the major direction to have an *E*-value not less than 8.3 GPa, with 96% of the 265 samples meeting the minimum requirements (Table 5). Distribution of *E*-values is shown in Fig 4. Summary statistics for salvaged lumber graded with the Metriguard are shown in Table 6.

Table 4. Percent of boards in visual grade categories according to National Design Standards for Douglas-fir–larch structural lumber grading (265 samples).

Grade	*E*-value (GPa)	Tested (%)
SS	13.1	51
No. 1 & Btr	12.4	5
No. 1	11.7	8
No. 2	11.0	10
Construction	10.3	9
No. 3/Stud/Stand	9.7	6
Utility	9.0	5
Below grade	<9.0	8

Although many boards had high stiffness, application of individual boards in structures will inevitably be determined by defects and condition, hence limiting the material available for structural use. CLT presents an opportunity to loosen structural and defect requirements by randomizing imperfections and working as a composite system either using all salvaged lumber or a combination of virgin and salvaged lumber. Still, any material intended for structural applications, whether working alone or in a system, should be extensively tested and understood, in accordance with design standards, before being widely accepted and used. In their recent study, Rose et al (2018) noted the importance of this information and highlighted the

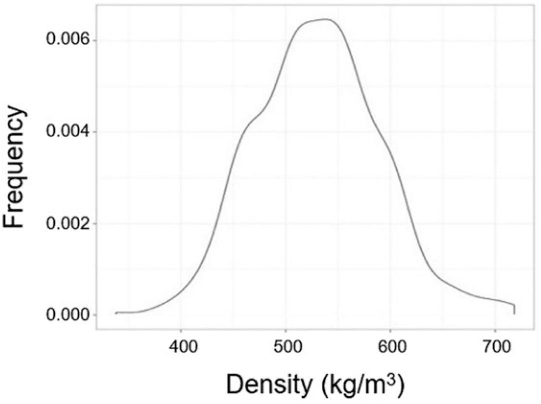

Figure 3. Frequency distribution for the density (kg/m^3) of 483 salvaged lumber pieces.

Table 5. Percent of boards in grade categories according to required Allowable Stress Design elasticity values for cross-laminated timber in the United States (265 samples).

Grade	*E*-value (GPa)	Tested (%)
E1	11.7	18
E2	10.3	9
E3	8.3	9
E4	13.4	45
V1	11.0	10
V2/V3	9.7	6
Below grade	<8.3	3

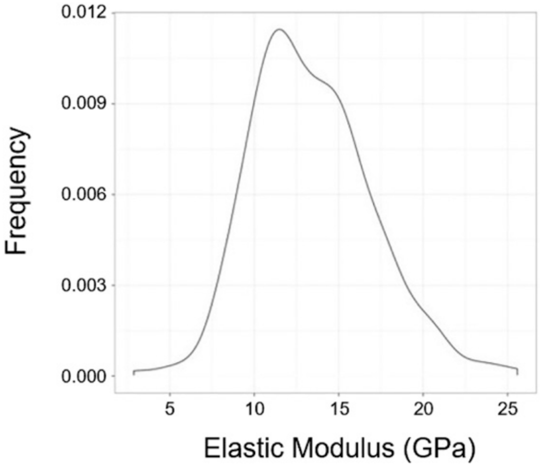

Figure 4. Frequency distribution of dynamic MOE (*E*) for 265 pieces of salvaged lumber.

need for further research to better understand salvaged ("secondary") lumber properties and variability.

The provision of wood property information for salvaged lumber is critical for the expansion of markets, and future research possibilities should examine different nondestructive, as well as destructive tests, for determining static MOE and MOR. In practice, it will also be important to assess the MC of recovered lumber to identify any pieces having high MC and in need for drying before reuse. A portable moisture meter would suffice for this purpose. In addition, because this population study only focused on rough-cut salvaged lumber from the Portland metro area, similar studies should be administered in different cities, for different species, on rough-cut and planed lumber, and on boards from various waste streams.

Table 6. Summary statistics for salvaged lumber MOE (GPa).

Metriguard grading statistics	
Average	13.6 GPa
Maximum	25.6 GPa
Minimum	2.9 GPa
SD	3.5 GPa
CoV	26%

CONCLUSIONS

Dynamic MOE of 265 rough-cut 38 mm × 89 mm (2 × 4) pieces of salvaged lumber were determined using a Metriguard Model 340 E-Computer. Over 50% of samples had a calculated stiffness equal to or greater than the highest structural design grade (Select Structural, 13.1 GPa) for Coastal Douglas-fir lumber. The presence of large knots and physical damage, present in 66% and 59% of boards, respectively, would likely downgrade boards, despite their acceptable MOE. In all, 96% of the 265 salvaged Douglas-fir boards graded using the Metriguard Model 340 E-Computer tested with a stiffness equal to or greater than the minimum stiffness required for use in the major direction of a grade E3 CLT panel ($\geq$8.3 GPa). Provision of wood property information for salvaged lumber is critical for market expansion, and this work represents the first characterization of lumber from deconstructed Portland, OR, dwellings.

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