FUTURE DIRECTIONS OF TIMBER ENGINEERING RESEARCH

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Abstract

This paper is an overview of current trends in timber engineering that are expected to influence the directions of future research. These include matters related to the structural use of sawn timber and engineered wood products. Factors that will affect this use include the increasing emphasis on performance-based design, system concepts, human factors, international trade, the special needs of developing countries and sustainability issues.

Keywords: Timber, Engineering, Research, Performance, Trade

INTRODUCTION

Sophisticated and extensive research into the use of timber as an engineering material has now been in progress for over 50 years and so there should be no surprises in the future. However, the building environment in which timber is used has changed considerably. New issues such as performance based regulations and sustainability have become very important; many new engineered wood products have been developed; and rapid innovation is essential to combat sudden changes in government regulations and the introduction of new competing materials.

An emerging issue arises from the fact that timber is a unique structural material in that it is well suited to applications both in cottage industries and in sophisticated engineering projects. The material requirements, particularly with respect to reliability, are quite different from these two applications. Yet rarely is the distinction made for these two applications with respect to quality control, design codes and construction practices.

ISSUES RELATED TO STRENGTH

Efficiency

A critical matter in the use of timber for structural purposes is the uncertainty in strength of timber and timber based elements. A schematic illustration of natural variability of strength (as measured by laboratory testing) is shown in Figure 1. The design strength is related to the 5-percentile value $R_{0.05}$. For large coefficients of variation, this can be considerably less than the mean value R_{mean} and accordingly there is considerable loss in structural efficiency, Table 1. For this reason a major consideration in the development of engineered wood products is to produce elements with low natural variability.

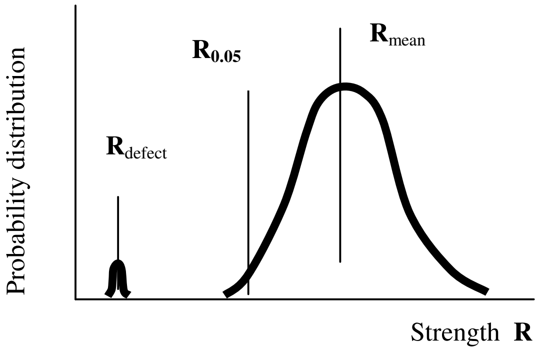


Figure 1. Schematic illustration of the strength distribution of a timber based element.

Table 1. Effect of variability on the efficiency of structural elements

Coefficient of variation	$R_{0.05}/R_{mean}$	
	Weibull distribution	**Lognormal distribution**
0.1	0.82	0.84
0.2	0.65	0.71
0.4	0.37	0.49

Rogue Defects

Another feature of structural timber elements, illustrated in Figure 1, is the possibility of the occurrence of a rogue element, with strength denoted by R_{defect}, which may have a strength considerably lower than the design parameter $R_{0.05}$, possibly even a strength value of zero. Even though such rogues may occur with a small frequency such as 1:1000 or 1:10000, this would be unacceptable if the element failure would lead to serious consequences such as the loss of life. Examples of such rogues would be the occurrence of compression shakes in softwood lumber or manufacturing defects in engineered wood. The detection of these rogues remains an ongoing research challenge.

An extreme example of concern for the occurrence of a rare fabrication defect was noted in the specification for the large glulam members used for the Sydney Olympics Exhibition Hall. This glulam contained about 2,000 finger joints in critical locations that would be subjected to high tension stresses in service. For satisfactory safety the fabricator would need to prove that his fabrication process was such that the chance of producing a finger joint of zero strength was far less than one in 20,000,000. The occurrence of such a joint in glulam would reduce the load capacity of an element by a factor of 5. Since it was not possible to detect such a rare defect, the solution chosen was to proof test every finger joint, an expensive undertaking.

Uncertainty

There is such a variety and number of structural elements it is not feasible to test every type of element for every possible mode of loading and failure. Accordingly, a theory is frequently used to predict the strength of untested failure modes. The effective coefficient of variation V_{eff} of the strength of such a mode is

$$V_{eff}^2 = V_{nat}^2 + V_{theory}^2 \quad (1)$$

where V_{nat} and V_{theory} denote the natural variability and the uncertainty of the prediction theory respectively. The coefficient V_{theory} typically lies in the range 0.1–0.5 [1] and as indicated by the numbers in Table 1, this can lead to very inefficient and at times unsafe design practices if inadequately assessed.

A particularly important application to this concept relates to the prediction of long term effects. Since all laboratory investigations are short term, an extrapolating theory must be used to predict long-term behaviour. Research for predicting this effect is particularly important for glue strength, termite attack and decay resistance [2]; [3].

Quality Control

Effective quality control is necessary if a structural element is to attain a reliable design strength; one way to achieve this is by continuous monitoring of the structural properties of production elements. Since structural strength can be measured only by destroying an element, the number of test samples tends to be kept to a minimum. This contradicts the quality control requirement that large sample numbers are required to make accurate measurements of the 5-percentile value $R_{0.05}$ if the coefficient of variation is large.

As an example, it has been found that the commonly accepted use of a test sample N = 5 for the daily check on the strength quality of stress-graded timber may be inadequate. If the coefficient of variation of strength is 0.45, then on average it will take about 3 months before a conventional CUSUM control system will trigger a halt in production following a strength loss of 20% in the strength properties of graded timber [4]. The development of more effective quality control systems is an urgent research matter.

SAWN TIMBER

Stress Grading

With the rapid changes that are occurring in the timber resource, there is an increased motivation for the development of effective methods of stress grading. With the aid of new scanning technologies, such as those utilizing lasers, microwaves, acoustic emission etc., there is the promise of more effective strength predictions. The value of such predictions is indicated by the correlation coefficient $r_{predict}$ that roughly relates the variability of ungraded timber $V_{ungraded}$ to stress graded timber V_{graded} by

$$V_{\text{graded}} \approx V_{\text{ungraded}} \sqrt{1 - r_{\text{predict}}} \qquad (2)$$

An increase in r_{predict} leads to a decrease in V_{graded} and hence an improvement in utilisation efficiency as shown in Table 1.

A further potential benefit from the current development of scanners will be the ability to grade for specific end-use products. For example, it will be possible to sort a parent population of timber into floor joist material (specified by stiffness requirements), truss material (specified by tension strength requirements) and stud material (specified by straightness requirements).

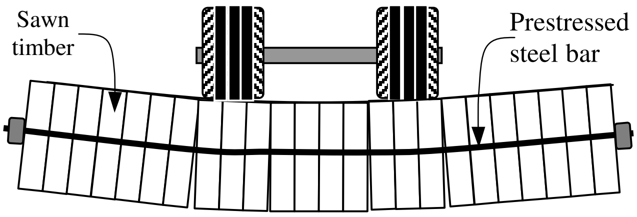
Variability

A problem with the use of sawn timber is the high variability of the material. However, if the sawn timber is used in a parallel system of *N* elements, then the effective coefficient of variation V_{eff} of the system is

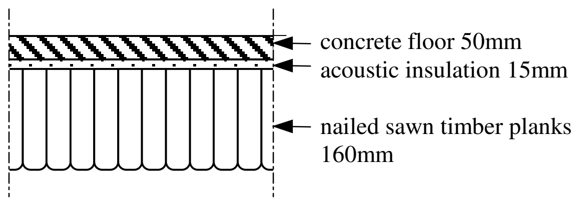
$$V_{\text{eff}} \approx V_{\text{graded}} / \sqrt{N} \qquad (3)$$

where V_{graded} denotes the coefficient of variation of the graded timber. This reduction in variability leads to an increase in structural efficiency. It also alleviates the detrimental effects of any rogue elements that may occur.

Two practical applications of the parallel system concept are shown in Figure 2. These are nail-laminated composite floor systems [5] and ‘stress-laminated’ bridge decks [6].



(a) stress-lam bridge deck system



(b) nailed-lam floor system

Figure 2. Examples of laminated composite systems.

Mechano-sorptive Effects

Mechano-sorptive effects have been studied in some detail and applied to predicting the creep deformation of elements. However, there has been comparatively little research on their effects on strength. Two examples in this regard relate to the long duration strength of lumber and notched elements [7]; [8]; [9]. Another potential and important practical application relates to the creep-buckling of structural elements [10];[11].

CONNECTORS

There are a few theories available for predicting connector strength. Examples are theories related to bolted joint [12];[13] and nail plates[14];[15]. However, these only cover simple failure modes. Most connector systems are assessed on the basis of test protocols, a procedure that has limitations as indicated in Section 2.

In assessing connector systems via test protocols, two major aspects still require solution. The first is the development of protocols for long duration and repeated loads. The second is the definition of failure for systems that develop excessively large deformations before peak loads, such as systems associated with bearing resistance.

ENGINEERED PRODUCTS

The term engineered wood products is generally taken to refer to both materials and building elements fabricated with wood as a dominant material.

There are three broad groupings of engineered wood products:

(i) *Structural elements cut from board or linear forms of homogeneous material*. Examples of these would be (a) slabs of Paralam, Scrimber, glulam, laminated veneer lumber, (b) board material in the form of plywood, oriented strand board, laminated strand lumber and (c) linear material such as finger-jointed lumber.

(ii) *Structural elements cut from slab, board or linear forms of composite material.* Examples of these include (a) boards of non-uniform layup, (b) sawn hardwood end-joined by metal plate connectors and (c) I-beams fabricated from a mixture of board and slab material.

(iii) *Composite elements fabricated as complete structural elements*. Examples of these would be the Gang-nail 'Posi strut' and the MacMillan 'Trus-joist'.

Examples of these three types of engineered wood structural elements are illustrated in Figure 3.

An excellent overview of engineered wood is given in the December 1999 issue of the journal *Timber and Wood Products International.* The explosive growth of these products is indicated by predictions that indicate their use will increase by a factor of 5–10 within the next 20 years [16];[17].

Probably the prime driver for composite construction is that it leads to structural elements that are much lighter and of longer lengths than is possible with sawn timber. For example, I-joists up to 20m long are commercially available. Other benefits include the increase in wood utilisation efficiency and also the structural reliability that comes with an engineered wood product.

The basic research needs related to engineered wood products, are related to the fact that they are susceptible to many possible failure modes, and that test protocols are required to assess the strength of all these failure modes. For example, for the I-joist shown in Figure 3b it is necessary to ensure that the joints in the web and flange will have adequate strength, regardless of which part of a beam they may occur in service; the long duration performance of all failure modes is also a research issue.

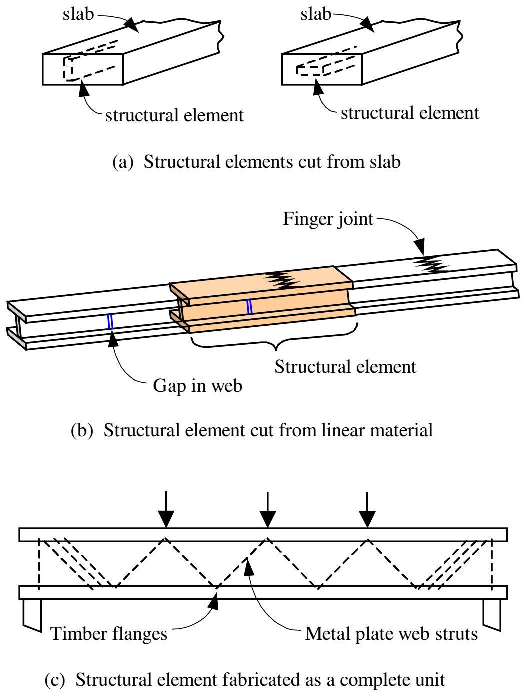


Figure 3. Examples of composite wood structural elements.

PERFORMANCE BASED DESIGN

Prescription and Performance

Probably the greatest driver of current research is the growing use of performance criteria in design. While prescriptive procedures specify how a structure shall be built, performance procedures specify how a structure should perform in-service.

Prescriptive procedures are simple to apply. However they are associated with several disadvantages. First, they are obviously a barrier to technical change. Second, the performance of a design is undefined and the safety level is uncertain. In addition it is not possible to optimise the design.

A major risk of prescriptive procedures is the fact that they are based on a combination of trial-and-error and experience, and this can sometimes lead to unacceptable risks when unusual situations occur. For example, when Cyclone Tracy (a cyclone with a return period of about 200 years) hit the Australian city of Darwin in 1974, most of the engineered buildings remained intact, whereas most of the houses (developed via prescriptive procedures) were destroyed. Within the newer suburbs, there was less than 5 per cent of the houses intact [18]. The exceptionally high wind pressures of Cyclone Tracy as illustrated in Figure 4, were well outside the recent experiences of house builders who developed housing technology by a trial and error process.

The following discusses examples of potential research related to the application of the performance concept.

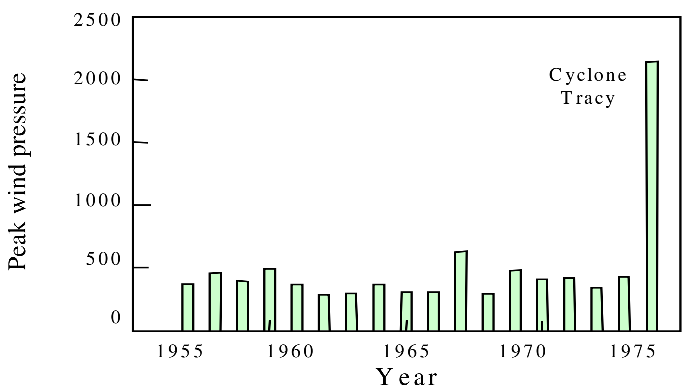


Figure 4. Annual peak wind gust pressures measured in Darwin.

Structural Safety

The risk of structural failure can now be computed by formal probability theory. An example of such an application, illustrated in Figure 5, was undertaken in 1986 to compare the effectiveness of the structural design codes at that time. It can be seen that the timber engineering code gave a reduced level of safety and so the code was subsequently modified. The challenge of future research will be to develop standard models for loads and strengths so that risk assessments may be applied quite simply and routinely to any innovative structural element or system. The modelling of durability and multiple mode failures are expected to be particularly difficult.

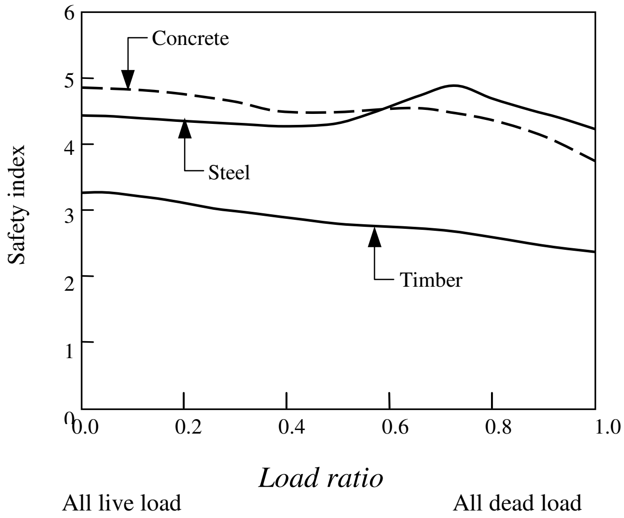


Figure 5. The computed safety of beam elements (Source: Leicester et al. 1986[24])

Building Fires

Prior to 1994, the building regulations of Australia would not permit the use of combustible material, including wood, in the fire resistant walls and floors used to separate the occupancies within a multistorey building. However with the advent of performance based regulations, the timber industry successfully argued that the performance target was the life-safety of the occupants and not the combustibility of fire resistant construction. Following the acceptance of this premise, the timber industry then produced risk analyses which showed that it is possible to design light frame timber construction that is as safe as acceptable reinforced concrete construction. An example of one such risk analysis is shown in Table 2; the building to which it refers is the three storey apartment illustrated in Figure 6. In this study the timber buildings denoted as Cases 14 and 15 were predicted to be associated with less risk to life than the acceptable reinforced concrete building denoted as Case 1. The result of this exercise was to enable timber to be used in fire separation walls for suitably designed buildings. The challenge for the future is to produce accepted risk models, so that analyses of types shown in Table 2 can be undertaken as a routine task by any qualified engineer. In particular, the sub-model used to predict evacuation times needs to be improved.

Table 2. Computer model predictions for building shown in Figure 2
(Source:Yung et al. 1994[25])

Case No	Structural frame material	Fire resistance* (min)	Central fire alarm	Sprinkler protection	Relative expected risk to life
1	Concrete	90	No	No	1.00
9	Timber**	20	No	No	2.27
14	Timber	60	Yes	No	0.90
15	Timber	60	No	Yes	0.67
* fire resistance of fire separation wall and floors ** conventional light timber frame construction					

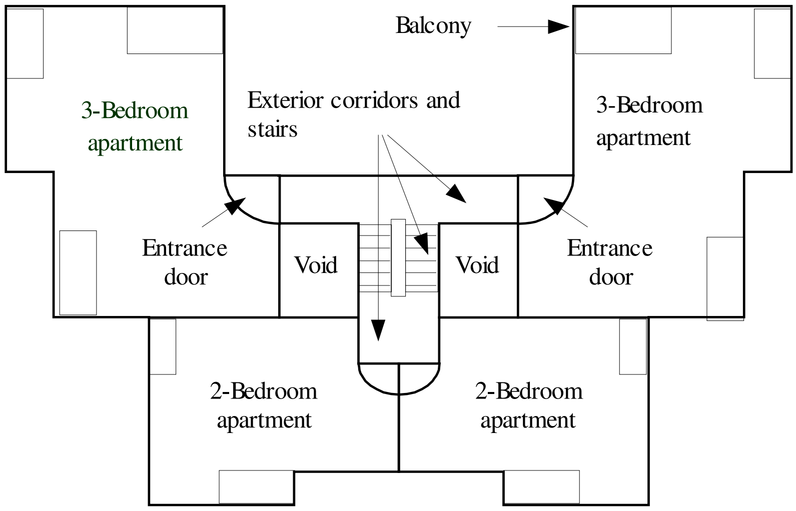


Figure 6. Plan of 3-storey apartment used for risk analysis.

Performance-based Building Regulations

Detailed descriptions and discussions on performance based building regulations have been given elsewhere [19];[20]. In Canada the term 'objective based regulations' is more commonly used.

The basic levels of control within a performance based regulation are illustrated in Table 3 by an example related to structural safety. It is important to note that while the performance requirements of building elements can be assessed in isolation, the way that these building elements are used within a design procedure must comply with the regulation objective, which invariably involves an estimate of the human acceptance of risk. The challenge to the researcher is first to define a regulation objective, and then to develop a design procedure to achieve this objective.

Table 3. Schematic example of performance based regulations

Regulation level	Example	Consideration
I. Regulation objective	Acceptable risk to life is $<10^{-6}$	Building element plus structural loads + human perception of risk
II In-service function	Probability of structural failure is $<10^{-4}$	Building element + structural loads
III Element performance	Acceptable probability of building element being under-strength is <0.05	Building element

Serviceability

Serviceability refers to the satisfactory function of a building, excluding aspects related to the risk of injury and death. In particular, structural serviceability refers to design for acceptable functioning related to floor dynamics, building distortion, building sway and element cracking.

Currently the design criteria used in designing for serviceability are essentially prescriptive. To remedy this situation, fundamental research is in progress to understand and quantify human perception. The first task is to define the perception of unserviceability according to sensory classes such as visual, aural and physical stimuli. Then it is necessary to quantify the stimuli within broad classes of intensity, such as levels of perception, annoyance, discomfort and fear. Finally it should be noted that many non-structural parameters will affect a human response to structural unserviceability. Examples of such parameters include the type of lighting of a wall containing a crack, the presence of straight reference lines when viewing distortions, the visibility or otherwise of the source of floor vibrations and finally characteristics of the observer involved. Some discussion on these matters has been given in a previous paper [21].

HUMAN FACTORS

Increasingly, it has become apparent that the modelling of human behaviour is an important aspect in design. The role of these models in design for building fires and for serviceability has already been mentioned. The conduct of maintenance activities is obviously an important component of durability models. The effect of human error in manufacture, design and construction will give rise to the rogue behaviour illustrated by R_{defect} in Figure 1. For all these reasons, it has become apparent that in the future application of performance-based concepts, the modelling of human behaviour will be considered to be as important as the modelling of material and environmental parameters.

TRADE

Many non-tariff barriers to trade in structural timber products exist because of special bilateral agreements between countries. Often design values are negotiated as part of a trade agreement package and not derived through performance evaluations. A way past unfair competition of this type can be found if the importing country has performance based building regulations. In such a case, an argument can be made that the commercial values of competing materials should be based on a comparison of their performance characteristics.

It should be noted however, that even if a performance base is accepted, there are still technical difficulties and regional differences to be reconciled [19]. One example, illustrated in Table 4, shows that performance evaluation procedures, even of such a simple product as sawn lumber, may differ significantly from one region to another. To overcome this difficulty, it would be desirable to develop simple procedures for establishing the equivalence between different assessment methods [22].

Table 4. Evaluated characteristic bending strength of 90 x 35 mm, F5 machine graded Australian Radiata pine

Method of evaluation	**Evaluated characteristic bending strength (MPa)**
European Standards	31.1
Australian Standards	38.5

DEVELOPING COUNTRIES

The two most pressing problems to be found in many developing countries are the requirement to utilise multiple species and the lack of effective quality control procedures.

The multiple species problem requires the development of techniques that are not species specific. An example of this has been the development of grading through proof testing [26]. In addition the use of structural grouping systems will simplify the production of design information. The problem of poor quality control can be alleviated by applying an adequate factor of safety to design properties, but to do this effectively requires local research.

Another matter of concem is that the procedures used by developed countries involve testing full size structural timber and the costs for this type of evaluation may be prohibitively expensive for use by developing countries. Table 5 illustrates that a cheaper method of evaluation is possible where the evaluation is based on testing small clear pieces of wood. This method is not as accurate as the method based on testing structural size timber, but it may be workable provided an appropriate penalty in design properties is accepted to compensate for the loss of accuracy in the evaluation procedure. For example, many developing countries in the tropics harvest hundreds of species of hardwoods, many of which have 2-3 times the strength of the commercial softwood timbers. For these countries, it is obviously cost effective to base design properties on testing small clear pieces of wood and to accept a penalty in design properties to compensate for the additional uncertainties involved. Probably the optimum action for developing countries may be to use small size clear wood testing combined with limited full size structural lumber testing to calibrate this procedure when applied to groups of species with similar structural characteristics .

Table 5. Comparison of two methods for evaluating the structural properties of timber

Test material	Cost for evaluation of one species	Laboratory time	Typical error in the characteristic strength estimates
Structural size timber	$10000 000	1 year	±5%
Small clear pieces of wood	$1000	1 week	±30%

SYSTEM EFFECTS

Many factors, such as the advent of performance-based concepts, has placed an emphasis on system analysis. It is insufficient to consider the structural design of an element or even a total building in isolation from consideration of other building performance criteria such as those related to fire resistance, thermal efficiency, building ventilation and air quality. For example air quality is affected by the type of glues used in engineering wood products. Furthermore, there is an increasing emphasis on building maintenance, life cycle assessment, energy efficiency and sustainability evaluations. New research is required to develop the necessary technology for including all these system effects in the design of a building, and also for monitoring the in-service performance.

Similarly, the efficient processing of structural timber will require the development of a system model and associated monitoring equipment to integrate the activities of forestry, log selection, cutting pattem, drying processes, grading and market activity.

CONCLUDING COMMENT

Future research related to engineered performance technology is essential for product innovation and for trade. Product innovation is particularly important as a means of coping with changes in resources, changes in regulations related to environmental concerns and changes in competition arising from the introduction of new building systems. Additionally it is quite likely that there will be an increasing trend towards the development of many new composite structural systems that combine wood with other materials so as to optimise the use of the available building material resources.

The most difficult aspect of engineered performance is the development of (probabilistic) models to be used in making quantified predictions of building performance. In addition, there are implementation difficulties associated with the fact that the target performance criteria are often quantified in terms of risk, and for many countries, there is a legal difficulty in stating that there is risk associated with a building design, particularly where that risk involves life safety.

Finally, mention should be made of at least one concern that will lead to new research in the near future. Studies to measure the ecological impact of human activity have demonstrated that the ecological footprint to support a single person in North America is about 4.5 hectares [23]. However the total useable land on this planet (including wilderness areas) tums out to be only 1.5 hectares per person. Consequently should all the people of this world aspire to the same standard of living as those in North America, and should we also wish to maintain our current plant and wildlife ecology, it will be necessary to increase our efficiency of land use by a factor of 5–10 times the current value. In these studies it was also found that the use of timber for building purposes contributes about 20 per cent of the total non-energy component of the ecological footprint. This is a significant portion of the footprint. It will undoubtedly result in pressure from society for an improvement in the efficiency of timber utilisation and consequently, to new research projects.

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