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Serviceability design of residential wood framed floors in Canada

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ABSTRACT

The serviceability design of wood-framed residential floors in Canada has taken a departure from use of the traditional deflection criterion based on maximum deflection under uniform loading. This departure is based on laboratory and field research in the 1970's and 1980's which, in 1990, led to adoption of a new criterion in the National Building Code of Canada. In part, this criterion is based on limiting the deflection of a floor system under the action of a concentrated load of 1 kN. This paper reviews the aspects of floor performance that a serviceability criterion is designed to limit, and the progress that has been made to extend the requirements to other than lumber joist floors. Research currently under way is designed to set the criteria within a broader dynamically based framework, and future research needs are outlined.

INTRDUCTION

The structural design of floors requires a designer to check capacity to carry design loads safely and rigidity to provide the level of performance expected in the intended occupancy. The quality of the building and the occupancy demands has always been reflected in expectations for serviceability. The more expensive the structure the greater the expectations regarding serviceability. The traditional serviceability design criterion for floors based on limiting deflection under uniform design loads (e.g., span divided by 360) was thought necessary to prevent cracking of plaster ceilings.

But serviceability means other things as well, namely limitations in vibrations that may be generated by the occupants. When clients found a particular floor design to be too bouncy, builders adapted their future designs to provide more satisfactory performance, usually by reducing the "code allowed" spans. The fact that bouncy floors can be found in practice implies that the traditional criterion used did not address all aspects of serviceability adequately and the builder or designer did not compensate for this.

Inadequate performance of an existing floor is problematic and sometimes very expensive to correct. Because it involves subjective opinions about structural serviceability that codes do not directly address this can result in expensive legal conflict. Some occupants of buildings prefer that the floor performance be so satisfactory that there is no noticeable floor response when loads move on them.

The degree of conservatism in design to achieve this can be accomplished but at some cost. In many cases that cost is small and it is worth it to secure a superior performance level. Use of a minimum performance criteria means that some people may not find the resulting performance satisfactory. On the other hand, a "code allowed" criterion for a type of occupancy assumes that there is some degree of tolerance for disturbances that might be noticeable in that occupancy, and some people might not be satisfied with the result.

The goal of research conducted on serviceability of floors is to propose criteria that will reduce uncertainty related to serviceability design so that the builders and their client/users are more likely to find the end results acceptable. When this goal is achieved, designers will provide better designed floors that achieve the desired level of acceptability at the least cost. To accomplish this requires study of the suitability of floors currently in use and correlating their acceptability with parameters that can be addressed in design. This paper reviews past efforts to provide better criteria for design of floors in Canada and the progress of work currently underway to improve them.

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WHAT A FLOOR PERFORMANCE CRITERION ATTEMPTS TO CONTROL

To understand what a criterion attempts to control, a general summary of the floor response phenomenon is required. For simplicity, we will concentrate mainly on the perception of the motion that occurs when loads (people) move on the floors in the occupancy.

In residential occupancies the normal movement of people going about their daily lives imposes forces on floors that vary in intensity and frequency. The presence of people or a person on the floor can radically alter the response of the floor because the person becomes part of the dynamic system that the two represent.

The behaviour can be “non-linear” because the effective dynamic properties of individuals change in unpredictable ways in the course of movement by a person and his/her physical characteristics and attitude. This is particularly true for short-span lightweight floors because the person’s mass is a significant proportion of the combined effective person/floor mass. An example of an extreme case of this is a person walking on a trampoline. On the other hand, for heavier longer span floors, the mass of the individual is small relative to that of the effective mass of the floor. Consequently, the person’s mass and damping characteristics affect the behaviour of the floor system to only a small degree.

Two distinctly different effects are noted in each of the above extreme cases. In the short-span light-weight floor case, the structure responds to the motion of the occupant in a way that is largely dependent on the energy content of the forcing function - the force/time history of the dynamically applied load. This ranges from nearly static to fully dynamic characteristic in that function. The ability of a moving person or another person in the vicinity affected by that motion to sense the motion depends on its frequency and magnitude.

In other words, if we represent the floor response at the position of a sensing person as an electrical signal, all frequency components from near DC and up may be perceived. For very flexible short span floors, the largest dynamic effects noticed relate to the load transfer a person makes from one foot to another in walking about the floor, which have a very low frequency content.

The perception of that motion is greatest by a seated person rather than by one that is standing or in motion. In a seated position, any tilt of the chair caused by relative displacements is also readily noted. Except for the magnitude of response, these movements have no relation to the natural frequency of the floor itself in an loaded or unloaded situation, but very much to do with the way that the mass of the moving person is transferred from one place to another across the floor.

At the other extreme, we have the case of long-span heavy floors on which the load transfer from one foot to another by a walking individual is not noticeable. The impact produced by the heel strike is responsible for the initiation of transient damped vibrations that persist long enough to be perceptible.

Between these two extremes lies a continuum of responses to a range of forcing functions that are all part of the normal occupancy loading. These may be created by one or more persons of any age, mass (weights), physical characteristics, and walking or running styles. To propose a rational yet economical set of criteria for design of floors having satisfactory performance is a significant task.

TRADITIONAL DESIGN CRITERIA FOR FLOORS

The traditional serviceability deflection limit was calculated as the maximum deflection of the floor under the action of the design live load as a ratio of the span. Commonly, the maximum permitted deflection has been L/360 where the span is defined as the quantity L. Since every joist in the floor was assumed to experience the same uniform loading, the design was performed as for a simple beam. Only the joist properties were required in calculating the maximum deflection. If composite action were assumed, the axial stiffness of the subflooring and the connection stiffness between the joists and the subflooring would have been used in calculating the deflection.

The loading was assumed to be 1.9 kN/m^2 (40 pounds per square foot), although this magnitude is rarely achieved in residential occupancies. Even though the load was unrealistic and the stiffness of the floor was under-predicted, the result was satisfactory for most cases. For design of traditional floors, the contribution of composite action was ignored because the field experience that led designers to assume the L/360 criterion was suitable already included that benefit. The calculation was originally based on no composite action - only the joist stiffness was assumed in preparing design tables used by builders.

The suitability of this criterion was based largely on traditionally constructed lumber floors that also had relatively short spans and which used was nominal 25-mm lumber subflooring. Changes in construction practices, including building larger houses, changes in lumber sizes, the introduction of plywood and OSB construction sheathing, new engineered wood products, fastening methods, etc., have led to a broader range of performance from poor to better to best, depending on the design and construction methods used. One example of this was, as late as 1972, use of 12.7 mm thick plywood was permitted for single layer combined underlay/subflooring. This minimum thickness was increased to 15.9 mm when a large number of minimum performance floors were built and the impact of this on overall floor performance was recognized.

In Canada, the L/360 deflection criterion has been used for many years for all spans of traditional floor construction. For sawn lumber joist floors at least, the spans were limited to the lengths of lumber available and other design considerations related to the size of the building and room sizes. Extension of spans beyond this experience base was only possible recently when engineered wood members became available. The continuing use of that criterion resulted in poorly performing floors. Some builders adapted to this by using a more conservative deflection criterion - say L/480 or L/600.

In the United States, until the early 1970's, the L/360 criterion for uniform loading was used for one- and two-family units of the Federal Housing Administration (later to become HUD) for spans up to 4.6 m (15 feet). Beyond this span the maximum deflection was limited to about 12.7 mm (0.5 inches) under the design load. This was eventually perceived to be too restrictive and the criterion reverted to the unrestricted use of a minimum of L/360 to all spans.

The previous two-limit application had an advantage not immediately recognized by the design community. The L/360 criterion addressed the then current experience base for short-span floors involving traditional construction. Beyond the 4.6 m span, where one might more likely perceive vibration transients, the span/deflection ratio became progressively larger and the designs became more conservative, limiting the floor response to less perceptible levels. For example, at a span of 30 feet the equivalent span/deflection design ratio would be 720 for the same design live load of 40 psf (1.9 kN/m^2). There was no formal evidence whether this level of conservatism was sufficient or not.

Of course, the design criterion promulgated in the USA and Canada did not address the effects that transverse flooring stiffness, floor mass, bridging or strongbacks have on the response of the floor to occupancy loadings. Consequently, it was still possible to build floors meeting those criteria yet not providing suitable performance. In some cases, builders either cut back permissible spans by one to three feet, or simply used the next larger joist size than the minimum size permitted, or a more conservative criterion (L/480 or L/600) than the minimum specified in the building code.

RESEARCH LEADING TO NEW CRITERIA FOR WOOD-BASED FLOORS IN CANADIAN RESIDENCES

Recognizing the limitations of the traditional design approach the Eastern Forest Products Laboratory in Ottawa [then part of the Canadian Forestry Service] undertook a longer-term study into this matter at the urging of wood products and building industries. There were two primary activities involved - field and laboratory testing of floors to validate an analytic computer model, and subjective evaluation of floors in occupied residences. This was to correlate acceptability with both computed and measured floor responses.

Static and dynamic tests of over 100 floors in occupied residences were carried out as well and innumerable tests on various floor assemblies in the laboratory (Onysko, 1988b). The main report on this work involved detailed study at 107 houses where formal consumer interviews and detailed inspections of the floor structures were performed (Onysko, 1985). The work resulted in a recommended tentative performance criterion based the maximum static deflection of floors under a nominal unit load of 1 kN.

The classification analysis of this database resulted in the tentative criterion shown in Figure 1. Although the computed response of a floor subject to an arbitrary dynamic impulse load also resulted in about equally successful discrimination between the acceptable and unacceptable floors, there was great uncertainty that the computed responses could be correlated with measured transient response.

At that time, both the measured peak response and frequency were insufficiently predictable to be used as reliable metrics of performance. As well, damping had to be assumed. In fact, it was found that the various test procedures used proved to be problematic in characterizing the dynamic performance of light framed floors in typical residences.

As described elsewhere the above tentative criterion was empirically based (Onysko, 1988a). In translating this tentative criterion to a recommendation for design of minimum performance floor spans, the criterion was shifted to a less conservative position to permit a specific common basic floor system to pass. That basic floor was a relatively short span floor that had been commonly found in floor construction in houses throughout the country.

The house building industry had urged that the criterion not be made so conservative that this common floor would not be allowed. The base floor performance on average, although not particularly desirable for the discriminating occupant, was considered reasonably acceptable. This was also confirmed over the period of the study by additional inspections in about another 500 homes. The modified criterion is provided in the following equations.

(a) $\Delta \leq 8.0/L^{1.3}$ mm for spans beyond approximately 3.0 m

(b) $\Delta \leq 2.0$ mm for spans under approximately 3.0 m

(c) $\Delta_{udl} \leq L/360$ m for all spans

where: Δ = floor system deflection under 1 kN (mm)

Δ_{udl} = the maximum deflection of a floor member under the action of a uniformly distributed load of 1.9 kN/m^2 [40 psf] based on bare joist properties.

L = joist span (m)

Although the expression for Δ is simple in character, it is not computationally simple to determine the floor system deflection under a concentrated load without recourse to a suitable computer program. The criterion and an approximate design approach, with related design tables, was adopted for Part 9 construction (principally residential construction) in the 1990 edition of the National Building Code of Canada (NBCC).

The calculation of the deflection is sensitive to construction parameters; i.e., it changes in relation to the fastening method, subflooring thickness, bridging and blocking, etc. This provides flexibility in meeting the users' needs, and offers an incentive for improved quality. However, it also makes the method more complex.

The same criterion was subsequently accepted in the 1995 edition of the NBCC, with modifications for additional construction variables. In addition, for both editions of the code, the Canadian Wood Council published accompanying tables to provide greater ease of use by builders (CWC, 1995). These tables expanded the number of assemblies that builders could select, while minimizing the number of tables that needed to be published in the formal code document.

The empirical basis of the criterion as stated above, is a database of floors of spans not greater than about 6.0 m (20 feet). The database encompassed the typical short span performance floors on which dynamic movement was closely associated with the non-amplified motion response to the footsteps of individuals on the floor. This non-amplified dynamic response can be represented by the static displacement response of floors.

The range of spans included in the study also extended into the transitional range where both deflection response and transient dynamic response were descriptors of the effects that occupants might experience. The inclusion of span (L) in the expression by the analysis reflected the influence of the transition from simple deflection response to situations that included perception of transient vibration.

The limitations of this criterion are (a) the mass of floors is not accounted for, (b) other properties unique to transient floor response, such as damping are also not accounted for. In part this was because the database itself did not include floors with concrete toppings, and most of the spans represented in the study were far shorter than the 6.0 m already mentioned. In any case, evaluation of damping and the dynamic test itself was problematic.

EXTENSION OF PART 9 CRITERIA FOR ENGINEERED WOOD PRODUCTS

Design tables for solid sawn lumber floors have always been featured in Part 9 of the NBCC. Engineered wood members are proprietary and design tables involving their use are typically prepared separately by each manufacturer using traditional design criteria. The provincial governments in Canada, having the power to adopt or adapt the NBCC, which is written as a model building code, made representations to the Canadian Construction Materials Centre (CCMC) to provide similar vibration controlled guidelines for these products.

All such products were already on file with CCMC, in the CCMC registry of product evaluations, as having met the structural qualification criteria. These products now had to show 'equivalency' to the vibration serviceability criteria in the NBCC for acceptance in the field. In 1995, on behalf of CCMC and through the co-ordination of the Canadian Wood Council, with support from manufacturers of proprietary engineered wood members, a project was undertaken to show how these products could meet the intent of the Code for vibration controlled floor spans.

This project dealt with a number of issues including the calculation of partial composite action, and the applicability of the Part 9 criterion to spans up to 10 m. There was concern about the substantial decrease in spans resulting from extrapolating the Part 9 criterion beyond the original experience base obtained in the mid 1970's. In the final report on this project, a modification was made to the Part 9 criterion for spans beyond 5.5 m to be more permissive than the extrapolation, although this was still more conservative that permitted minimum practice (CCMC, 1997). The resulting criteria are shown on Figure 2, and are provided below.

(a) $\Delta \leq 8.0/L^{1.3}$ mm for spans between 3.0 m and 5.5 m,

(b) $\Delta \leq 2.55/L^{0.63}$ mm for spans between 5.5 m and approximately 9.9 m,

(c) $\Delta \leq 0.6$ mm for spans beyond approximately 9.9 m

(d) $\Delta \leq 2.0$ mm for spans under approximately 3.0 m

(e) $\Delta_{udl} \leq L/360$ m for all spans.

The concluding report on the study also provided a detailed analytic method for computing the static point load response of floors without necessary recourse to detailed computer model. This analytic method was calibrated to the results of analyses by the computer program that was originally developed for the earlier EFPL and Forintek Canada Corp. field and laboratory testing and which was also used as a basis for the design expressions provided in Part 9 of the NBCC.

Some limitations to this criterion have become apparent in the short time it has been applied. On the whole there has been a reasonably good feedback for conventional light framed engineered wood floors. However, there are some questions as to whether the modifications made to the Part 9 criterion were sufficiently conservative.

Because the criterion does not explicitly include dynamic response, the modification may allow effects that the Part 9 criterion only partly compensated for. This may have been compounded by allowing the effect of bridging, installed to reduce both the static concentrated load deflection and the uniform load deflection, to increase spans beyond the experience base.

Effectively, the modified boundary beyond 5.5 m did not appear to lead to floors of equal acceptability. In the same way, the L/360 or L/480 override on uniform load deflection, which tended to govern floors with concrete topping, also inadequately compensated for the dynamic performance that actually resulted. Also, if composite action is used to increase floor spans beyond the limits of either the Part 9 or L/360 or L/480 criteria, the performance may be further reduced.

The 1960's experience with open web steel joists supporting concrete floors led to more conservative design recommendations showing that the traditional criterion was insufficiently conservative (AISI/CISC 1997, Allen and Murray 1993). Changes to the modified criterion shown in the above equations are currently being contemplated for this class of floor as an interim measure until more encompassing criteria can be adopted.

CURRENT WORK ON FUTURE FLOOR PERFORMANCE CRITERIA

In 1993-94 a research plan to study the dynamic performance of floors was proposed and adopted at the Eastern Laboratory of Forintek Canada Corp. [the privatized laboratories of the Canadian Forestry Service]. This program built upon the previous field work in several ways. The test program included both static and dynamic testing. The dynamic tests included both shaker testing, and a particular ball drop test. Both the forcing functions and the responses of the floor were measured and stored for modal response analysis. The most important achievement of this test program is that there has been a substantial representation of longer span floors with concrete toppings, some of which have proved to be unsatisfactory. Altogether, the study has provided an additional number of 130 floors that yield additional insight into the performance of short and longer span floors. Using the field floor database and logistic regression, several forms for a tentative criterion were generated. An additional database of 49 floors was used to test these tentative criteria. The validation results are very encouraging. The simplest form of the tentative criterion using 1 kN static deflection and fundamental natural frequency as criterion variables performed the best. More details about the work can be found in a project report (Hu 2000). Analytical techniques for some of the additional performance parameters are being developed to propose performance criteria and provide design procedures.

NEEDS FOR ADDITIONAL PERFORMANCE CRITERIA

We started out this paper with a reminder that stated minimum performance criteria are intended to represent a tolerable level of acceptability for a particular type of occupancy. The study of these phenomena was possible in residential occupancies because of the large number of such buildings available and the likelihood that some of the floors assemblies produced did not perform well.

The residential class of occupancy does not normally receive the detailed scrutiny of structural consultants. On the other hand, homebuilders are willing to adopt new construction techniques, if they are assured that these techniques will improve the quality of the end product. To do this, homebuilders need more information on how to achieve incremental value by enhancing floor construction.

Commercial buildings receive the scrutiny of structural designers understanding the requirements of a particular client, so there is greater likelihood that structural performance will meet expectations, and if it does not, it is likely that the matter will be resolved one way or another to the satisfaction of the client. It is difficult to find a sufficient number of unsatisfactory floors of this type to be able to obtain sufficient data needed as a basis for issuance of design criteria based on consumer responses.

Certain commercial occupancies are likely more costly to build and the serviceability expectations are correspondingly higher than in typical residential occupancies. The structural loadings are also higher, reflecting anticipated occupancy and dead loads. Criteria for these floor applications require special consideration, but may be facilitated by adapting the emerging criteria mentioned above, and by comparing the designs resulting from use of those criteria with current satisfactory designs.

Continuous joist floors occupy a particular market niche that can be quite important economically for some manufacturers. These possess some additional performance characteristics that are not addressed in the current emerging performance criteria. Separate investigation and subjective calibration will be required to adapt the emerging criteria based on the extensive field studies of simple span floors. In a similar way, the adequacy of the supporting structure becomes more critical to the performance of continuous joist floors and this must be addressed through a separate investigation.

Floors which depend on composite action with other materials may also require durability considerations. The most obvious example of this case is floors with concrete toppings. Some toppings may delaminate from the base wood floor, or may break up when wetted. When separation and cracking of the topping occurs, the floor behaves differently and the basic wood-based supporting floor must bear the burden of the additional dead load and suffer the consequences in its dynamic behaviour. Construction parameters that lead to durable connection and reliable performance are needed. If they cannot be assured, such floors should be designed assuming complete de-bonding, and with the extra mass accounted for in the frequency and response function calculations.

Nailed floors can become over-worked by foot traffic. Shrinkage as a result of drying of construction moisture has the same effect. This working can lead to loosening of the subflooring and other materials. When this occurs, the floors become livelier than when first constructed. Field gluing with suitable construction adhesives has been found to result in suitable reliable attachment between these elements. Field gluing also helps to limit floor squeaks.

CONCLUSIONS

The above review described a work in progress ranging from the past traditional design criteria for floors that formed the basis for design in many countries, to new criteria leading to improved serviceability. The experience gained and the feedback provided by the industry has been invaluable. While past practice in codes has been to specify minimum criteria, there is some merit to providing such criteria in terms of a degree of acceptability. A basic minimum may still be required, but optionally higher or "better " quality levels might also be provided if the probability of satisfaction associated with those levels could be quantified to allow designers some degree of choice. Beyond the near term, we foresee the development of companion criteria for support beams and continuous floor systems.

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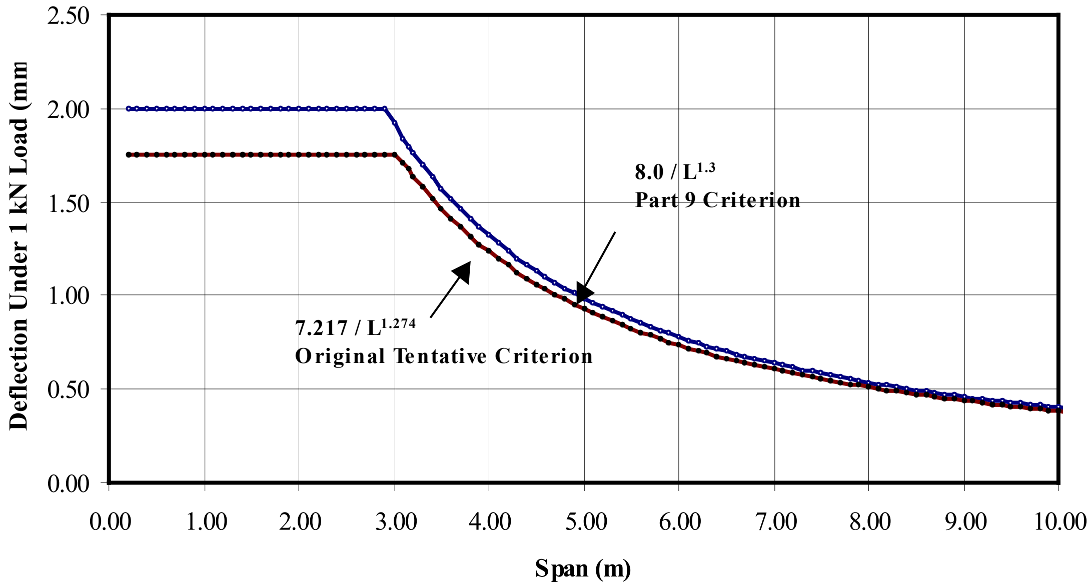

Figure 1: The Part 9 criterion and the criterion based on the original database (from Onysko, 1985)

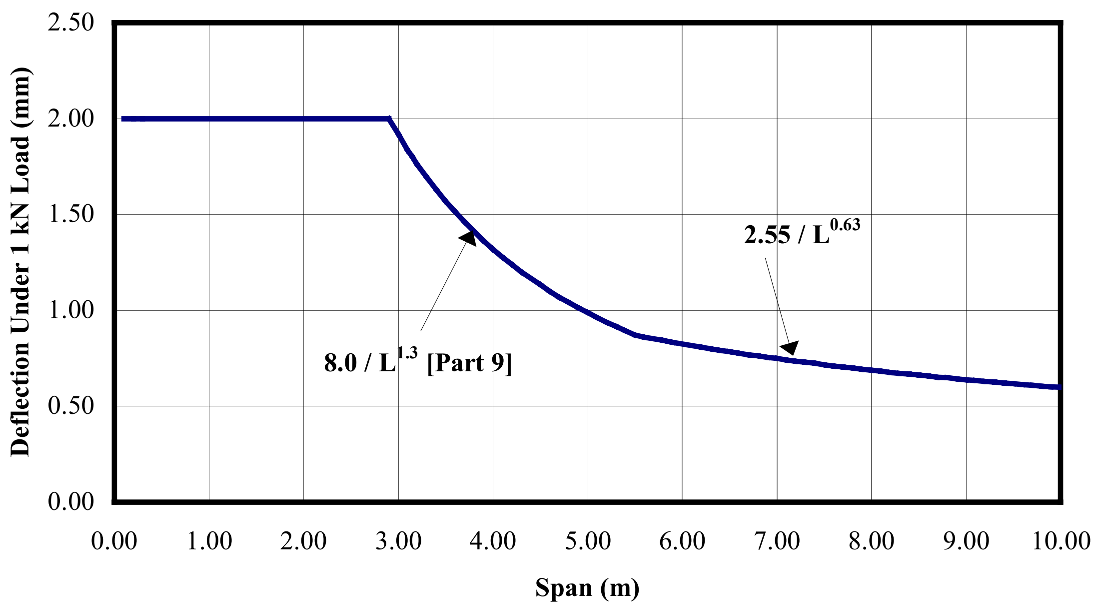

Figure 2: The modified Part 9 criterion for spans over 5.5 m (CCMC, 1997)