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VIBRATION SERVICEABILITY DESIGN ANALYSIS OF CROSS-LAMINATED-TIMBER FLOOR SYSTEMS

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ABSTRACT: Vibration serviceability of various types of timber floor systems has claimed much attention during past decades. Yet the definition of robustly reliable engineering design approaches has remained elusive, except in well-defined situations. Successful design depends on having appropriate vibration serviceability performance assessment criteria, and ability to predict floor response parameters used by those criteria. This paper addresses prediction of dynamic response characteristics of cross-laminated-timber (CLT) floor systems using finite element methods. Attention is focussed on systems that contain realistic construction features like intra-slab CLT panel to-panel joints, and variations in floor slab edge supports. Modelling assumptions are verified by comparing analytical predictions with test results.

KEYWORDS: Cross-laminated-timber, Design, Dynamic response, Joints, Support conditions, Vibration serviceability

1 INTRODUCTION

Vibration serviceability of lightweight floors constructed from wood-based or other materials has received much attention during the last several decades. This reflects the proneness of such substructures to high amplitude motions in the frequency range that is annoying to humans. Mostly R&D has been directed toward predicting the behaviour of floors constructed using parallel arranged joists of various types, and definition of construction improvements for such systems [e.g. 1-8]. Suggestions have been made for how to design joisted timber floors, resulting for example in inclusion of provisions in Eurocode 5 [9].

In Canada prescriptively defined maximum spans of floor joists in houses and other small buildings are partly based surveys of occupant satisfaction with vibration responses of floors [10]. There is no formal requirement to incorporate vibration serviceability as part of engineering based design of floor joists. Consequently engineers and joist product manufactures employ a range of methods aimed at avoiding construction of floors having unsatisfactory dynamic responses. Methods employed range from simple limitation of static deflection to criteria intended to limit peak acceleration and bounciness [1-4,7,11-15].

Despite the existence of some required and optional vibration serviceability engineering design methods, a drawback is that they are all empirically based and therefore only applicable to well defined situations. Although this status quo suffices for traditional applications of timber floors, it does not provide a generalized basis for avoiding vibration serviceability problems. It follows that engineers do not have robustly reliable capability to design floor systems for non-traditional applications or use of non-tradition Engineered Wood Products (EWP).

Successful engineering vibration serviceability design depends on having appropriate performance assessment criteria, and ability to predict response parameters used by those criteria. The issue of performance assessment criteria has received much attention directly or indirectly in the context of timber floors [1-4,16]. Currently suggested performance assessment criteria require that engineers be able to predict one or more of: out-of-plane response natural frequencies; peak velocity or peak acceleration caused by a defined dynamic excitation; and static deflection under a defined gravity force.

Discussion here addresses prediction of dynamic responses parameters by analytical methods in the context of cross-laminated-timber (CLT) floor

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systems. The focus on CLT reflects that it is a class of shallow profile EWP that has become popular for construction of large floor systems in applications formerly beyond the capabilities of timber solutions. In many instances CLT is used as a substitute for Reinforced Concrete (RC) slabs. Therefore expectations of building owners and occupiers tend to be that CLT floors will have performance characteristics equal to or better than those of equivalent RC floors.

Primary advantages of using CLT relate to its relatively low mass, and the easy and rapidity of on-site operations when components have been pre-cut off-site [17-20]. However, there can also be disadvantages associated with using CLT. Unlike with RC, it is difficult to create monolithic slabs from CLT simply because of need to make edge-to-edge connections between discrete pieces within floor systems or other substructures. Current industry preferred types edge-to-edge CLT connections are those based on half-lapped or spline joints, Figure 1. Use of half-lapped or single-spline connections facilitates site construction, and is efficient in terms of minimizing material wastage.

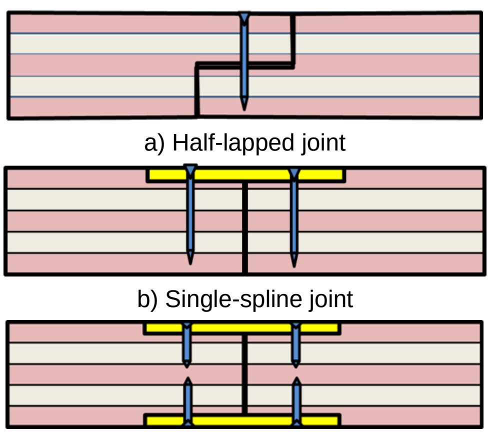

Figure 1: Commonly preferred edge-to-edge CLT connection methods

Seen from a structural engineering perspective there is need to consider how connection characteristics influence static and dynamic responses of complete floor systems. This need is illustrated by an experimental study at the University of New Brunswick (UNB) on CLT slabs having intra-slab half-lapped connections [21]. It was found that such connections with the increased width can cause clustering of out-of-plane modal frequencies, which may amplify motions of slabs to levels that affect vibration serviceability adversely.

The remainder of this paper assesses ability of analytical models to correctly predict key dynamic response parameters that are the basic inputs to any of the suggested vibration serviceability assessment criteria for lightweight floors.

2 CLT PROPERTIES

The material stiffness and damping properties of CLT utilized in analyses described here apply to Nordic X-Lam manufactured in Canada [22,23]. Values were derived from full-scale vibration tests data collected at UNB [21], and information in the literature [18,24-27]. The approach taken was to assume that CLT plates behave as homogenous orthotropic slabs. Dynamic elasticity constants were determined by inverse analysis so that modal frequencies of thick plate bending slab models matched free vibration responses of single rectangular shaped CLT panels. It was also assumed that CLT has a uniform density. Table 1 summarizes estimated material properties which become values used to predict behaviours of floor systems. To note is that for a 175mm thick CLT panel with a simply supported span of 5.5m (i.e. length of the calibration panels) the design would be controlled by the manufacturer adopted vibration serviceability performance criterion for buildings having residential or mercantile occupancies.

TABLE 1: *Apparent properties of CLT used in dynamic analysis of floor systems**

Property	Units	Value
Thickness, t	mm	175
Density, ρ	kg/m^3	520
Elastic moduli:		
E_1	GPa	10.75
E_2	GPa	10.00
E_3	GPa	6.00
Shear moduli:		
G_{12}	GPa	0.725
G_{13}	GPa	0.040
G_{23}	GPa	0.073
Poisson's ratios		
v_{12}	--	0.44
v_{13}	--	0.30
v_{23}	--	0.30
Viscous damping ratio, μ	%	0.84

* Nordic X-Lam: in-plane dimensions: 5.5m parallel to face laminations (direction 1); 2.28m perpendicular to face laminations (direction 2). Direction 3 is perpendicular to plate.

3 FINITE ELEMENT FLOOR SYSTEM MODELS

3.1 SCOPE AND OBJECTIVE OF MODELS

Finite element (FE) approximation models were constructed to replicate full-scale laboratory-built floors tested at UNB. The arrangements considered incorporate single and double CLT panels having two or four edges supported. In double panel tests intra-slab (panel edge-to-edge) connections have half-lapped joints similar to that shown in Figure 1a.

This fits with the overall objective of creating verified CLT slab modelling techniques, which can then be used to predict dynamic behaviours of other floor systems. Therefore, what is presented here is intended as a basis for understanding what modelling features are essential for reliable application of vibration serviceability design criteria. It is also a benchmark for credibility of proposed simplified design analogies [e.g. 18].

3.2 MODELLING TECHNIQUES

Finite element models were built using the COMSOL Multiphysics commercial software package [28]. Each CLT plate is represented by 388 predefined fine triangular plate bending elements having material properties in Table 1. The mesh also includes 54 edge elements and 4 vertex elements. Figure 2 illustrates the FE mesh for a single CLT plate having in-plane dimensions of 5.5m by 2.28m. Half-lapped joint plate edge-to-edge connections are represented as hinge connections, reflecting that they have ability to transfer in-plane force flows and out-of-plane shear force flows in floor slabs, but not ability to transfer slab bending moments [21]. Line supports represent CLT plates bearing directly on tops of steel beams, as can occur in building multi-storey building superstructures. All references here to hinge connections in FE models mean that there is enforcement of translational continuity, but no enforcement of rotational continuity between elements along hinge-lines in FE models.

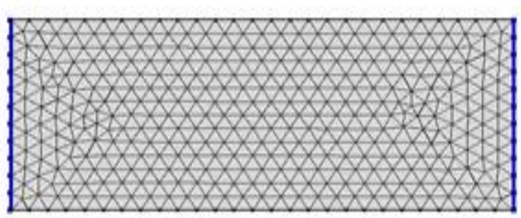

Figure 2: Finite element mesh for a single CLT panel (388 elements)

In the case of single CLT panel systems, the slab end boundary conditions varied between line hinge supports (restrained against vertical and horizontal translations, free rotation about hinge-line) and fully fixed ends (all translations/rotations restrained). Transverse edges of single panel slabs varied from fully free to point supported against vertical translation at centre span.

Dimensions of plate elements was decided based on iterative mesh refinement that was carried out until eigenvalue solutions produced stable estimates of modal frequencies up to 140Hz.

3.3 REPLICATION OF FLOOR TESTS

3.3.1 Tests programme

Test results used to verify modelling techniques pertain to 175mm thick CLT that matches the material properties in Table 1. Construction variations enabled consideration of effects of altering the plan areas and span-to-width (aspect) ratio, and effects of altering boundary support conditions. It should be noted however that changing the width also leads to incorporation of a half-lapped joint hinge-line connection at mid-width. That half-lapped connection has 160mm long self-tapping screws placed at a spacing of 300mm. For the experimental work of the 5-ply CLT plates only the conditions of 2 edges supported were tested. Variation was in the support material: steel (I-beam flange top) and timber (lumber between plate and steel beam).

Previous investigations on traditional joisted timber flooring systems had found that altering the degree of end fixity generally had little effect on dynamic responses of floors [4,8]. Therefore it was investigated, as part of the tests, whether this is also true for CLT floors but the effect was minor [21]. The data used here is for CLT held down to steel support beams using G-clamps.

Operational Modal Analysis (OMA) was carried out to obtain the dynamic response characteristics of floor systems [29], with extracted parameters including mode shapes, modal frequencies and effective modal viscous damping ratios. This was done using the ARTeMIS Testor 2011 and Extractor 2011 software programmes [30,31], and analysing data by frequency and time history domain techniques. The modes discussed here are ones having frequencies up to 90Hz, with those being the ones that could be reliably identified. Although higher order modes have been widely ignored by past researchers, the information about them is in fact important for holistic study of how construction alterations affect modal response characteristics of structural systems. Matched analytical predictions of responses of examined test setups extend beyond the 90Hz range for the same reason.

3.3.2 FE floor models

Four FE models were generated as follows:

1- Single panel with end hinge supports (*S-2end*)
2- Single panel with end hinge supports with three points supported against vertical translation (*S-2end/3VT*)
3- Single panel with end fully fixed (*S-Fixed*)

4- Double panels with end hinge supports with three points supported against vertical translation (*D-2end/3VGT*)

For the *S-2end/3VT* case each transverse edge was supported against vertical translation at end and centre breadth positions, which was considered to replicate the test situation. In the *D-2end/3VT* case the panel edge-to-edge connection was simulated as a hinge-line (i.e. having ability to transfer thrust forces and moment normal to the hinge-line). Support conditions were treated as in the case of *S-2end/3VT* with the three vertical translational restraint points positioned to encompass the increase in width. Other model representations of the panel edge-to-edge connection were examined but not found suitable.

3.3.3 Effect of edge support conditions

Table 2 compares predictions of modal frequencies obtained for analyses 1 to 3, which represent effects of altering single panel floor support conditions. It is difficult, arguably impossible, to actually clamp ends of CLT slabs in ways that approximate a built-in situation similar to what is achievable with RC. Therefore the *S-Fixed* case is an approximation to the behaviour of an interior span of a multi-span CLT slab. Case *S-2end* replicated the test case in which the edge of the floor was free and could bounce on the support and *S-2end/3VT* replicated the test case in which the floor edge was held down to prevent it from bouncing. Therefore despite the simplicities of the arrangements there is some wider generality to the conclusions that can be drawn.

Table 2*: Predicted modes and modal frequencies for single CLT panel floor systems*

Mode*	Modal frequency (Hz)		
	Analysis case		
	S-2end	*S-2end/3VT*	*S-Fixed*
1,1	11.1	12.2	20.7
1,2	17.0	18.5	24.0
2,1	37.8	38.6	46.1
2,2	43.8	45.2	50.9
3,1	70.3	70.8	75.8
3,2	75.6	76.6	81.0
1,3	95.4	95.6	96.4
4,1	104	104	107
4,2	109	110	113
3,3	123	124	125
5,1	138	138	140

* Mode *i,j* signifies order of mode shape parallel to span (*i*) and perpendicular to span (*j*)

Although it should be self-evident, the comparison highlights the need to realistically represent slab boundary conditions in any analysis intended to predict low-order out-of-plane modal frequencies. This has however not always been done in past applications of vibration serviceability criteria to evaluation of timber floors, with use of room size having been recommended instead of the actual structural span and geometry [1,2,12,15]. It might be argued that in some situations, like light-frame construction use of room size is an acceptable surrogate for the true span. But, recent OMA studies on multi-storey light-frame superstructures has proven that even such limited claims are not correct [32].

The particular analyses summarised in Table 2 imply that it is not particularly important to distinguish between *S-2end* and *S-2end/3VT* support situations. However, it would be wrong to extrapolate and create conclusions about lack of importance of representing CLT panel edge support conditions properly in other situations (e.g. interior floor slab supports running perpendicular to span). Similarly it would be unwise to conclude that proposals to ignore intra-slab panel edge-to-edge continuity are valid [18]. Hints to need to avoid unreliable deductions of the types mentioned here exist in the slight, but nevertheless important disparities between low-order modal frequencies for cases *S-2end* and *S-2end/3VT*. In other cases the influences of edge support alterations can be much stronger and alter modal mass and stiffness considerably as illustrated by case *S-Fixed* with about 84% and 70% increase in fundamental frequencies respectively over cases *S-2end* and *S-2end/3VT* respectively.

Table 3*: Comparison of modes and modal frequencies* for single and double CLT panel floor systems with ends supported*

S-2end/3VT		***D-2end/3VT***	
Mode	*Frequency (Hz)*	*Mode*	*Frequency (Hz)*
1,1	12.2	1,1	11.9
1,2	18.5	1,2	14.1
2,1	38.6	1,3	21.4
2,2	45.2	2,1	38.6
3,1	70.8	2,2	40.5
3,2	76.6	2,3	57.5
1,3	95.6	1,4	69.3
4,1	104	3,1	71.2
4,2	110	2,4	72.6
3,3	124	3,2	82.5
5,1	138	3,3	85.0
--	--	1,5	100
--	--	3,4	104
--	--	4,1	105
--	--	4,2	106
--	--	5,1	138

** Only frequencies ≤ 140 Hz shown*

Although not the intent of this brief study of edge support conditions, results do highlight the importance of underpinning test-based deductions about importance of changes in construction arrangements with analytical explanations.

3.3.4 Effect of floor width and aspect ratio

Table 3 compares predicted modal frequencies and mode shape types for the *S-2end/3VT* and *D-2end/3VT* cases.

Doubling the floor width, and therefore halving its aspect ratio and at the same time introducing a hinge line at mid-width, has several important influences on modal characteristics.

The first important influence is that increasing floor slab width lowers the fundamental modal frequency (mode 1,1). This is because across-width change in the mode shape decreased the ratio of modal stiffness to the modal mass. In terms of practical design this illustrates that suggested simplified methods of predicting fundamental natural frequencies of CLT slab systems [e.g. 18] cannot be generally valid. Second, the number of mode shapes that need to be considered increases when the floor aspect ratio is reduced. This has important implications relative to generality of design practices that require prediction of the number of modes with frequencies lying below a certain cut-off value. For example, the design method in Eurocode 5 requires prediction of the number of first-order modes having frequencies of 40Hz or less [9]. Third, when floor width is increased there is greater tendency toward clustering of modal frequencies. Such clustering can result in modal frequency separations (or harmonics or sub-harmonics of those) that match frequencies to which humans can be sensitive [14]. Another consequence of modal clustering is that it may amplify motions that occur under forced or free vibration conditions. Fourth, when floor widths are incremented by addition of replicating edge-to-edge jointed panels some higher order modes will match those of a single panel system. For example, both *S-2end/3VT* and *D-2end/3VT* cases exhibit closely matching modes 2,1, 4,1 and 5,1. But this does not mean that the cases match in total. This phenomenon also highlights the possibility of non-trivial far-field motion transmissions in large floor slab systems, or even non-trivial motion transmissions between storeys of medium- or high-rise buildings.

3.3.5 Comparison of test and model results

Results in Table 3 add support to the conclusion that simplified vibration serviceability analyses cannot be reliable, unless applied to relatively trivial problems. Striking amongst the tabulated analysis results is that adding a second CLT panel to a system changes the number of modes with frequencies less that 60Hz from four to six; and that the frequency of mode 1,3 reduces from 95.6Hz to 21.4Hz. Other analyses not reported here further emphasize the great sensitivities that can exist in floor slab responses to common construction variations.

Tables 4 to 6 compare test and FE model results for mode types and associated frequencies, for floor types *S-2end*, *S-end/3VT*, and *D-2end/3VT* cases respectively. The FE analyses correctly predict the number, types and sequences of modes for each of the studied cases. In absolute terms all differences between predicted and observed modal frequencies are quite small, or in most cases negligible.

Table 4*: Case S-2end: test versus FE model modes and modal frequencies*

Mode	Modal frequency (Hz)			
	Test	*FE model*	*Difference*	
			Absolute	*(%)*
1,1	11.4	11.1	0.3	2.6
1,2	17.9	17.0	0.9	5.0
2,1	37.5	37.8	0.3	0.8
2,2	44.2	43.8	0.4	0.9
3,1	67.1	70.3	3.2	4.8
1,3	91.6	95.4	3.8	4.2

** Single CLT panel with ends supported*

Table 5*: Case S-2end/3VT: test versus FE model modes and modal frequencies*

Mode	Modal frequency (Hz)			
	Test	*FE model*	*Difference*	
			Absolute	*(%)*
1,1	12.0	12.2	0.2	1.7
1,2	19.7	18.5	1.2	6.1
2,1	41.7	38.6	3.1	7.4
2,2	51.4	45.2	6.2	12
3,1	77.7	70.8	6.9	8.9
1,3	91.8	95.6	3.7	4.0

** Single CLT panel with two edges supported*

Table 6*: Case D-2end/3VT: test versus FE model modes and modal frequencies*

Mode	Modal frequency (Hz)			
	Test	*FE model*	*Difference*	
			Absolute	*(%)*
1,1	11.5	11.9	0.4	3.5
1,2	14.3	14.1	0.2	1.4
1,3	19.2	21.4	2.2	11
2,1	39.8	38.6	1.2	3.0
2,2	44.7	40.5	4.2	9.4
1,4	62.2	69.3	7.1	11
3,1	71.0	71.2	0.2	0.3
2,4	78.2	72.6	5.6	7.7
3,2	82.8	82.5	0.3	0.4
3,3	88.2	85.0	3.2	3.6
1,5	91.6	100	8.6	9.4

** Double CLT panels with ends supported*

Discrepancies between predicted and observed modal frequencies are direct consequences of the simplifications representation of end and edge support conditions, and simplified representation of the intra-slab hinge connection in the case of system *D-2end/VT*. Although not reported in detail here, supplemental FE analyses were carried out that showed that disparities in natural frequencies can be narrowed to negligible levels if support conditions and intra-slab connections are modelled in more complicated ways. Necessary refinements are introduction of spring and link elements at support and connection locations. Although adding model complexity is not particularly difficult, it seems a level of sophistication unlikely to match what design engineers are likely to consider justified. Plus, the authors consider the predictions of mode types and frequencies obtained to be sufficiently good for confident application of the same modelling techniques in other analyses of CLT slab systems. They plan to apply the approaches in, for example, sensitivity analyses aimed at definition of classes of design situations where vibration serviceability is likely to be problematic, and classes of situation not prone to such problems.

Tables A.1 and A.2 in the appendix to this paper provide comparisons of mode shapes extracted from the test data [21] and those predicted by FE models, for cases *S-2end/3VT* and *D-2end/3VT*. As the figures in those tables illustrate, agreement between predicted and measured mode shapes is generally good. Minor discrepancies in predicted shapes are consequences of aforementioned simplifications incorporated into the models. Therefore those discrepancies can be eliminated, but again the cost is addition of arguably unwarranted complexity

4 GENERAL DISCUSSION

The content of Section 3 does not directly address question of using FE models to predict floor response characteristics like peak velocity or peak acceleration under defined types of dynamic excitation. This omission is justified, because if tools like the COMSOL Multiphysics software package [28] accurately predict modal characteristics of systems, they also will reliably predict time history responses and therefore accelerations and velocities under defined excitations.

It is important to bear in mind that what is stated here about necessary complexity of models for vibration serviceability analysis is a function of specifics of the type of CLT slabs considered. Therefore the statements have to be viewed contextually and not taken as generalizations.

Creation of floor systems having poor out-of-plane dynamic response characteristics can be the consequence of poor solution definition. Sometimes no amount of analytical complexity, or increasing the amount of material employed, will be able to overcome consequences of poor solution definition. Therefore although it is important to have reliable vibration serviceability design criteria and reliable methods of estimating parameters used by those criteria; it is equally important to properly select solutions. To illustrate, many examples of poorly performing timber floors are the consequence of introducing high levels of disparity between the flexural rigidities of floors in parallel and perpendicular to span directions [3-5]. This is well recognized and why many efforts have been directed toward creation of bridging methods that increase the across-joists flexural rigidities of joisted floors [5-7]. Technically, it is actually the ratio of floor stiffness in parallel and perpendicular to span directions that is important, rather than the corresponding ratio of flexural rigidities but the latter is often an acceptable surrogate for the former. If the ratio of flexural rigidities were to be unity then a floor will behave as an isotropic slab.

Except when their plan geometries are complex or highly elongated, isotropic slabs exhibit good separation of their model frequencies [33], which greatly decreases proneness to amplification of motions under forced or free vibration conditions. It follows that if slabs have isotropic plate response characteristics relative simple vibration serviceability design criteria can be successfully applied in design. In fact, this is essentially the reason why simple design methods are normally adequate for RC slabs [34], but not for timber or some other types of lightweight floor systems. Unfortunately there is no possibility of a universal simple vibration serviceability design method being found for timber floor systems. However such a Holy Grail may be possible for timber floor construction methods that result in approximately isotropic plate dynamic responses. Studies at UNB beyond the scope of the present discussion are developing practical ways of creating CLT slabs that behave as close approximations to isotropic slabs.

The broad message to be drawn from these general comments is that it is perfectly feasible to design and construct high performance floors using CLT slabs, or indeed any other timber floor construction method. Doing that depends on to adopt appropriate construction methods, and application of proper engineering design criteria and analysis methods. To slightly rework a well-worn saying “The devil is in the construction detailing” and that detailing is what controls both dynamic responses of constructed systems and how engineers must predict those responses.

5 CONCLUSIONS

It is quite feasible to model the vibration response of CLT floor slab systems with construction details typical of actual practice. However, accurate and complete calculations are only possible if models are realistic. Discussion here helps define what realistic means. Conversely this discussed does not support propositions that have been made for application of simplified design criteria and analysis methods.

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APPENDIX: COMPARISONS OF TEST AND PREDICTED MODE SHAPES

Table A.1: *Case S-2end: test versus FE model modes shapes*

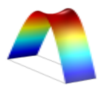
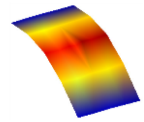
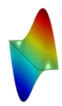
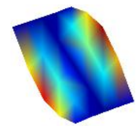
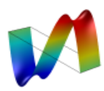
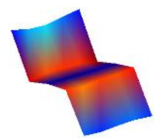
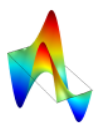
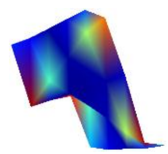
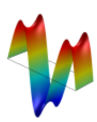
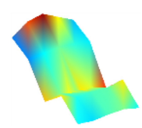
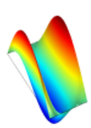
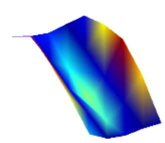
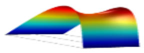
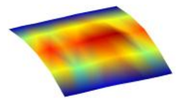
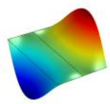
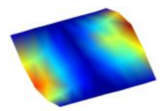
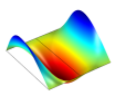
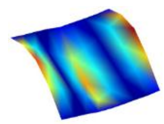
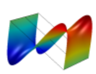
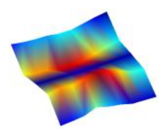
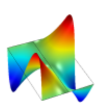
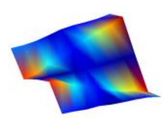
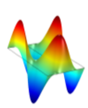
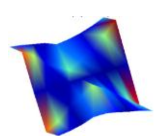
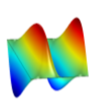
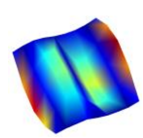
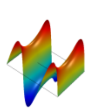
Mode	FE model		Extracted from test data	
	Freq. (Hz)	*Shape*	*Freq. (Hz)*	*Shape*
1,1	11.1		11.4	
1,2	17.0		17.9	
2,1	37.8		37.4	
2,2	43.8		44.2	
3,1	70.3		67.1	
1,3	95.4		91.6	

***Table A.2**: Case D-2end/3VT: test versus FE model modes shapes*

Mode	FE model		Extracted from test data	
	Freq. (Hz)	*Shape*	*Freq. (Hz)*	*Shape*
1,1	11.9		11.5	
1,2	14.1		14.3	
1,3	21.4		19.2	
2,1	38.6		39.8	
2,2	40.5		44.7	
2,3	57.5		49.1	
1,4	69.3		62.2	
3,1	71.2		71.0