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DEVELOPMENT OF REDUCED SCALE MODELS OF TIMBER STRUCTURES WITH DEDICATED SIMILITUDE LAWS

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Abstract

The complex mechanical behaviour of wood structure has to be tested experimentally. However, the size of wooden structural elements is sometimes too high for experimental test beds, in particular for projects of medium and high-rise building that are emerging worldwide. Experimental investigation cannot be made on this kind of structure due to technical constraints. By the way, tests are realized on reduced scale models whose properties are chosen thanks to a dedicated similitude law. A similitude law is a set of scalar (called scale ratio) which link the parameters of the reduced scale structure with the full scale ones.
Due to the non-linearity and non-homogeneities of wood structures, the sizing of reduced scale mock-ups is particularly challenging. Reduced scale mock-ups could be non-representative of full-scale structure because of instabilities, different modes of failure, or high uncertainties. The objective is to find a methodology which optimize reduced scale mock-up representativeness and that take into account experimental constraints.
A reduced scale model of medium rise timber structure was on a shaking table with an earthquake signal to assess its capacity to dissipate energy. This test highlighted the difference between the expected scale ratio and the experimental ones. To understand the origin of these differences, several tests was conducted on connectors and bracing frames at different scales to compare theoretical and experimental scale ratios. This study lead to a methodology to size efficiently reduced scale structure to improve their representativeness.

Keywords: Similitude laws, Structural dynamics, Timber structures, Experimental method,

1.Introduction

Wood buildings represent a performant answer for sustainable cities and ecological transition. An increasing number of countries aims to develop the market share of wood buildings for their environmental benefits. Timber buildings, especially high-rise structure, are sensitive to wind-load or other vibration load (railway, vehicles…) that can cause discomfort to inhabitants due to high acceleration. Therefore, the dynamic of this kind of structure is not well known because of the complex material non-linearities, damping and energy dissipation specific of wood construction.
Experimental tests are necessary to understand the complex dynamical behaviour of civil engineering structure. However, the dimension of a building is not suitable with lab experiments in most cases. To be able to study such buildings, a way is to test a representative reduced size mock-up using similitude laws [1], [2]. The objective of this paper is to define a methodology to build representative reduced size mock-up.

A similitude laws is a set of scale factor λ_x that link the parameters of the reduced scale mock-up with those of the full-scale structure:

$$\lambda_x = x^F / x^R \tag{1}$$

With x^F and x^R the values for the parameter x respectively related to full-scale structure and to the reduced scale one.

Similitude theory has been developed for a long time in fluid mechanic [3] with the traditional use of adimensional parameters and in aerospace sector [4]–[6]. In civil engineering, some recent studies presented similitude laws for mechanical and seismic tests on large structures [7]–[10].

The most classical way to determine a similitude law is to use dimensional analysis (DA) [1], [11]–[14]. The parameters of the reduced model must follow the Vaschy-Buckingham Theorem [11]. It does not require the knowledge of behaviour equations of the structure but only the relations between the main parameters. In general, as there are more parameters than equations, several similitude laws can be chosen depending on experimental constraint.

A seismic test on a reduced timber structure was conducted in 2017 and showed the limit of the representativeness of reduced scale structures built with the dimensional analysis. To understand accurately the differences between real and theoretical scale factors, several mock-up of connectors and bracing structures were studied at different scales. These experiments will help to build a specific methodology for the sizing of reduced timber structure.

2.Sizing of a reduced mock-up

2.1 An example: Silva Tower

Silva Tower is a project of a high-rise timber building in Bordeaux, France. With its 18 floors, it will be one the highest timber building in the world without a concrete core. Due to the lightness of the wood, this kind of structure can be particularly sensitive to dynamical loads such as winds and earthquakes. Several tests took place in the FCBA laboratory to investigate the dynamical behaviour of wind bracing elements used in this project. This mock-up did not represent the whole structure but only a section of three floors representative of the structure at a 1/3-scale without interior works. This reduced scale structure had a timber frame structure with a CLT (Cross Laminated Timber) core and A-shaped bracing frame as seen in Figure 1.

Figure 1 - Reduced mock-up of a section of the SILVA Tower with additional mass (concrete blocks)

The structure was sized using dimensional analysis. The scale factor for acceleration was to one (which is necessary in order to ensure that gravity scale factor remain equal to 1). This similitude law is called acceleration law. The other factors of interest are then deducted (see Table 1).

Table 1 - Scale factors obtained with acceleration law

Parameter	Dimension	Scale factor
Length	$[L]$	λ
Section	$[L]^2$	λ^2
Volume	$[L]^3$	λ^3
Time	$[T]$	$\lambda^{\frac{1}{2}}$
Frequency	$[T]^{-1}$	$\lambda^{-\frac{1}{2}}$
Acceleration	$[L][T]^{-2}$	1
Velocity	$[L][T]^{-1}$	$\lambda^{-\frac{1}{2}}$
Mass	$[M]$	λ^2
Force	$[M][L][T]^{-2}$	λ^2
Stiffness	$[M][T]^{-2}$	λ
Stress	$[M][L]^{-1}[T]^{-2}$	1
Young Modulus	$[M][L]^{-1}[T]^{-2}$	1
Damping factor	$\emptyset$	1

Note that the scale factors for volume and mass are not the same. By the way, in order to respect the similitude law used, it is necessary to add mass on the mock-up. It was realized by using concrete block on each floor that can be seen on Figure 1. The scale factor of one for young modulus implies that the material properties remain identical between the different scales. This condition is not perfectly respected for wood structure because of the heterogeneity of wood material. Finally, instability (buckling, brittle damage) and non-linear phenomena (shock, friction) are not taken into account into the similitude law.

2.2 Results and issues

The structure was loaded with a seismic signal from Guadeloupe [15] at an increasing amplitude. The test was stopped for an acceleration of about 1g because of a brittle failure of a wood-metal assembly of the CLT core.

Some of the parameters of the connectors did not respect exactly the similitude law, because of uncertainties or technical constraints. Indeed, as an example, it is not possible to reduce the steel plate of connector without risking buckling instabilities. That is why the properties of the assemblies (such as stiffness and resistance) and those of all reduced structures are not perfectly similar as illustrated in Table 2.

Table 2 - Real and theoretical scale factor for the SILVA tower mock-up

Parameter	Full scale value	Reduced scale value	Theoretical scale factor	Real scale factor
Maximal Force	$370 - 420\ kN$	$59 - 68\ kN$	9	$6.2 - 6.3$
Maximal stress	$4.2 - 4.8\ N/mm^2$	$6 - 6.9\ N/mm^2$	1	0.7

Even if the structure had a very good seismic behaviour – the brittle fracture occurred for a signal six time higher than the worst earthquake measured in metropolitan France – its q factor[1] is lower than expected.

The scale reduction had thus changed the failure mode of assemblies. Failure modes are are often non-linear with the scale of the structure. During the test, we observed that a brittle fracture of a connector occurred at the same time than the ductile deformation of the diagonal connectors. Therefore, the reduced structure may had a less effective dissipative behaviour than the full structure.

Besides the uncertainties were not estimated. However, the fabrication process had not the same relative tolerance between a full-scale structure and a reduced one, it could be easily predicted that the similitude law will magnify the defects. Moreover, as the wood material and wood-metal assemblies are non-homogeneous and non-linear, it could also put into question the representativeness of the reduced structure.

This first test showed the limit of the scale reduction used here for the study of a wood structure. In order to improve our characterization of the type of structures using similitude laws, special attention must be put into the scale reduction and the evaluation of uncertainty propagation for wood structures.

In order to do so, several connectors and bracing frames were tested at different scales to improve the methodology of sizing reduced structures with similitude laws. A timber frame structure, similar to the bracing frame of the SILVA tower, was designed for this project and is represented in Figure 2. Firstly, the behaviour of the assembly of the V-shaped diagonals was tested. Their specific geometry, with three bolts, was adjusted to be compatible with our experimental means.

[1] The q factor is defined in European norms by the ratio between the experimental near-collapse acceleration and the computed design acceleration.[16], [17]. It represents the complex energy dissipation of the system (damping, friction, plasticity, shocks) with a single scalar parameter.

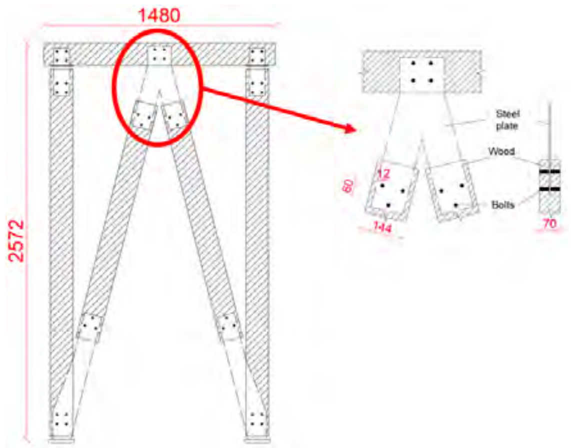


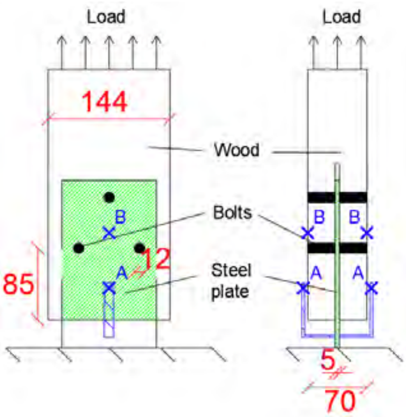
Figure 2 - Structure and connectors

3.Experimental studies on connectors

3.1 Presentation of the experimental configuration

Firstly, an isolated connector of the structure was tested at three different scales: the full scale that is broadly representative of existing dimensions, and two reduced scales mock-ups with dimensional scale factors respectively equal to 1/2 and 1/3.

Monotonic and cyclic tests were conducted according to EN NF 26891 [18] and EN NF 12512 [19]. Load was applied in tension and compression. The relative displacement between steel plate and wood (respectively A and B on Figure 3) was measured.



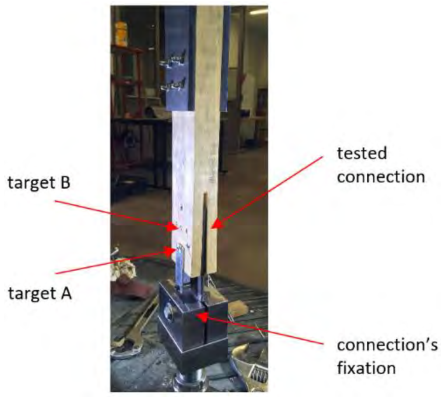


Figure 3 – (Left) Scheme of a wood-metal connector. (Right) Connector instrumented during a tensile test.

For the monotonic tests, the displacement imposed was such as presented in Figure 4. The displacement increased with a constant velocity until load reach 40% of a theoretical ultimate force $F_{u,th}$. Then the displacement is stabilized during 30s (B-C), decrease until load reach 10% of $F_{u,th}$ (C-D) is stabilized one more time during 30s (D-E), and increases until fracture (E-F). For cyclic tests, the chosen displacements signal had a triangular shape with an increasing amplitude (Figure 4). This amplitude depends on the displacement δ_y that represents the displacement for which the connector starts to yield and is identified thanks to the monotonic test. Three cycles were realized for each amplitude for each connector. The displacement was increased until the structure failure.

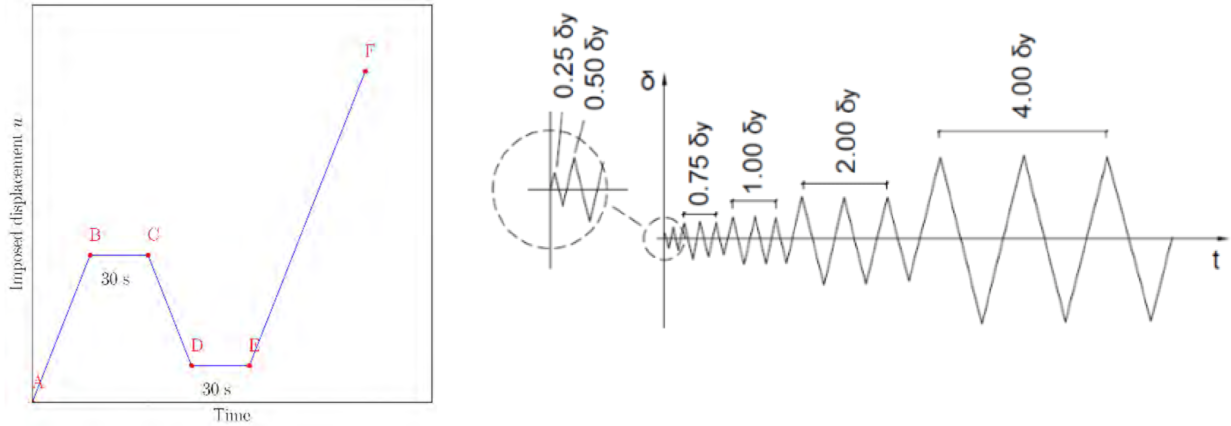


Figure 4 - Imposed displacement for monotonic test (left) and cyclic test (right)

3.2 Main characteristics determination

Several parameters can be obtained thanks to both monotonic and cyclic tests. Indeed, we evaluate with monotonic tests the elastic stiffness K_e, the ultimate force F_u and the ultimate displacement u_u and with cyclic tests gives us the dissipation factor ν_{eq}.

Figure 5 shows the elastic response of a full-scale connector for a monotonic and a cyclic test. The elastic behaviour of these connectors is strongly non-linear (Figure 5) so it is hard to define an elastic stiffness value. In accordance to the norm EN NF 26891, the elastic stiffness K_e was defined as the slope of the load displacement curve during the charge/discharge step (i.e. the slope obtained by linear regression between A and B on Figure 5). The ultimate force F_e and the ultimate displacement u_u are identified on the first point before a force decrease (point C on Figure 5). The equivalent damping ratio is calculated for a given amplitude according to the EN 12512 [19] as the ratio between energy dissipated and potential energy (Figure 6).

Other parameters could be identified, for instance initial stiffness or ultimate force for cyclic test but they seem less critical for the sizing of the full-scale connector.

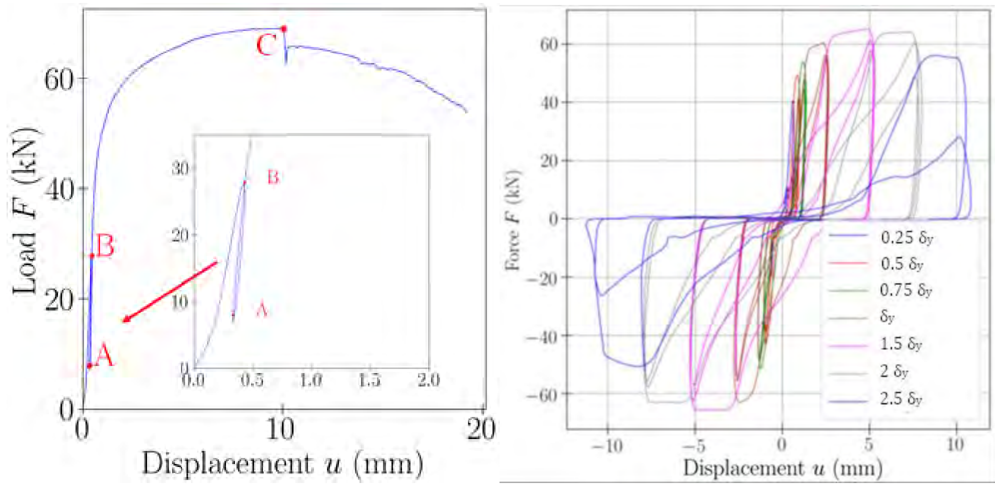


Figure 5 - Load-displacement curve of a monotonic test and a cyclic test on a full scale connector

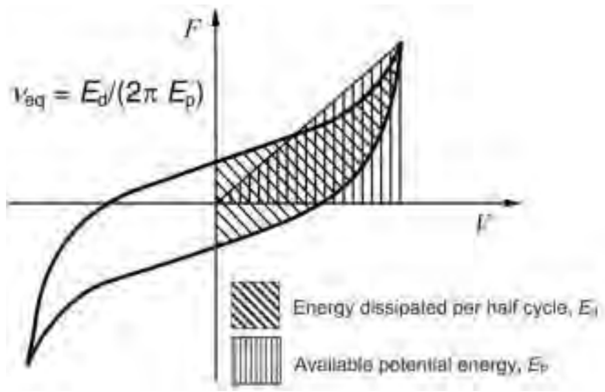


Figure 6 – Estimation of the equivalent damping ratio ν_{eq} as calculated in accordance to [19]

The value of these parameters are given on the Table 3. Experimental scale factors were obtained by calculating the ratio of the mean values of each parameter at each scale.

$$\overline{\lambda_x} = \overline{x^F}/\overline{x^R} \tag{2}$$

With $\overline{x^F}$ and $\overline{x^R}$ the mean values of the parameter x measured experimentally respectively for the full-scale assembly and the reduced scale assembly. Its standard deviation σ_{λ_x} can be expressed by the following equation:

$$\left(\sigma_{\lambda_x}\right)^2 = \left(\frac{\sigma_{x^F}}{\overline{x^R}}\right)^2 + \left(\sigma_{x^R}\frac{\overline{x^F}}{\left(\overline{x^R}\right)^2}\right)^2 \tag{3}$$

With σ_{x^F} and σ_{x^R} the standard deviation of the parameter x measured experimentally respectively for the full-scale assembly and the reduced scale assembly.

Table 3 - Main parameters identified for wood-metal connectors at different scales

	Full scale		1/2 reduced scale		1/3 reduced scale	
Number of tests	8		9		10	
Variable of interest x	Mean $\overline{x}^{(F)}$	CoV* (%)	Mean $\overline{x}^{(R)}$	CoV (%)	Mean $\overline{x}^{(R)}$	CoV (%)
Elastic stiffness K_e (kN/mm)	185	9.51	86.0	18.9	45.0	19.2
Strength F_u (kN)	69.5	8.26	19.7	7.32	8.87	5.86
Ultimate displacement u_u(cm)	9.9	9.9	5.9	13.2	3.4	11.4
Equivalent damping ν_{eq}* (%)	12	16.7	15	20	11	18

Table 4 - Theoretical and experimental scale factor of main parameters of wood-metal connectors

	1/2 scale			1/3 scale		
Characteristic x	Theoretical scale factor $\lambda_x^{(th)}$	Experimental scale factor $\overline{\lambda_x}^{(exp)}$	CoV (%)	Theoretical scale factor $\lambda_x^{(th)}$	Experimental scale factor $\lambda_x^{(th)}$	CoV (%)
Elastic stiffness K_e	2	2.18	25.3	3	3.93	26.7
Strength F_u	4	3.53	10.9	9	7.82	10.1
Ultimate displacement u_u(cm)	2	1.68	16.5	3	2.91	15.1
Equivalent damping ν_{eq}*	1	0.8	26	1	1.1	24.6

* The equivalent damping is given for a signal amplitude of δ_y

The equivalent damping had a high coefficient of variation that can explain the difference between experimental and theoretical scale factor. However, the difference between theoretical scale factor and experimental ones for elastic stiffness, ultimate displacement and maximal strength cannot be explained exclusively by uncertainties.

3.3 Distortions for wood-metal assemblies

During this experiment, some of the failure at full scale were due to ductile failure of metallic pins while other were due to brittle fracture of wood. For reduced scale experiment, all the failure mode of assembly were due to ductile failure of pins. Reduced mock-ups cannot respect a perfect similitude law with the full-scale structure. Indeed, some geometrical aspects are difficult to produce at a reduced scale (for instance the thickness of metallic plates). However, one of the main hypothesis for the use of dimensional analysis is the linearity and the homogeneity of the system. However; wood material is non-homogeneous and has a nonlinear elastic behaviour. Moreover, friction and local plasticity in metal-wood contact zone also occur and are non-linear phenomena. Due to all of this, mode of failure are dependent of the scale of the assembly. All these phenomena affect the experimental scale factor and can interfere with the identification of main characteristic of wood assemblies with a reduced scale model.

After evaluating the behaviour of wood-metal connectors, wooden frames were also studied.

4. Experimental studies on wooden frames

4.1 Presentation of the experimental configuration

The same methodology was used on wooden bracing frames at different scales. The bracing frame is represented on the Figure 7 at full scale (2.5m tall, representative of common structure) and reduced scale (1/2 and 1/3).

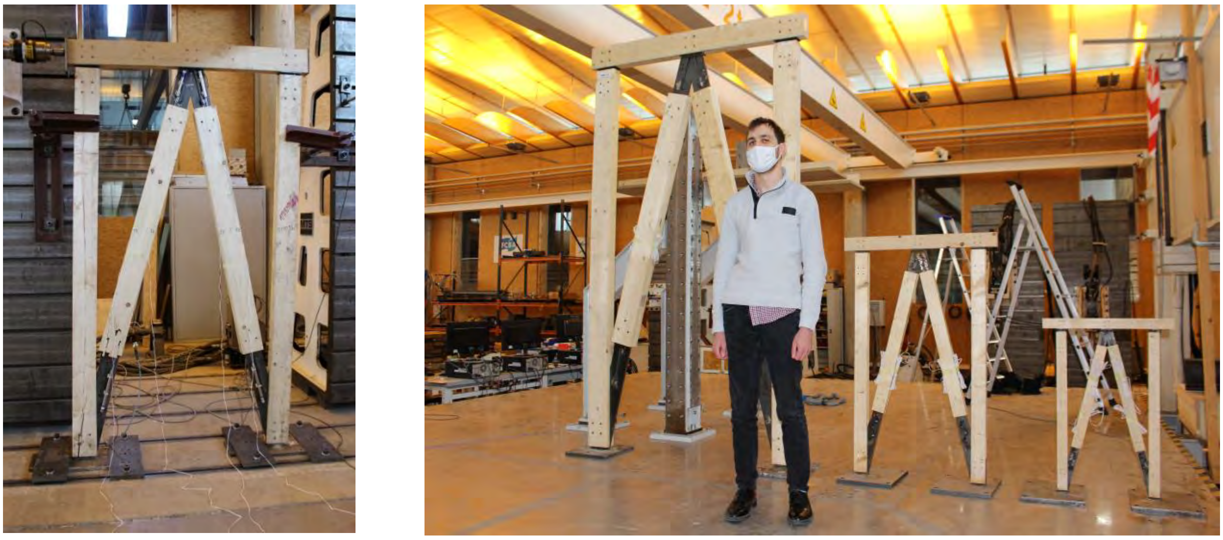


Figure 7 - Bracing frames: (Left) Shape (Right) at different scales

Monotonic and cyclic tests were conducted on these structures with the same methodology as the assemblies. The load was applied on the top left of the structure and the displacement was measured with a laser sensor at the top right of the structure. The signal shape is the same as the one presented in Figure 4 with higher test velocity to keep the same test duration. Some examples of experimental results are given on Figure 8. Displacements were measured on the head of the frame. LVDT was placed on each assembly of the diagonals to measure the relative displacements. Finally, strain gauges was placed on the mid-length of diagonals.

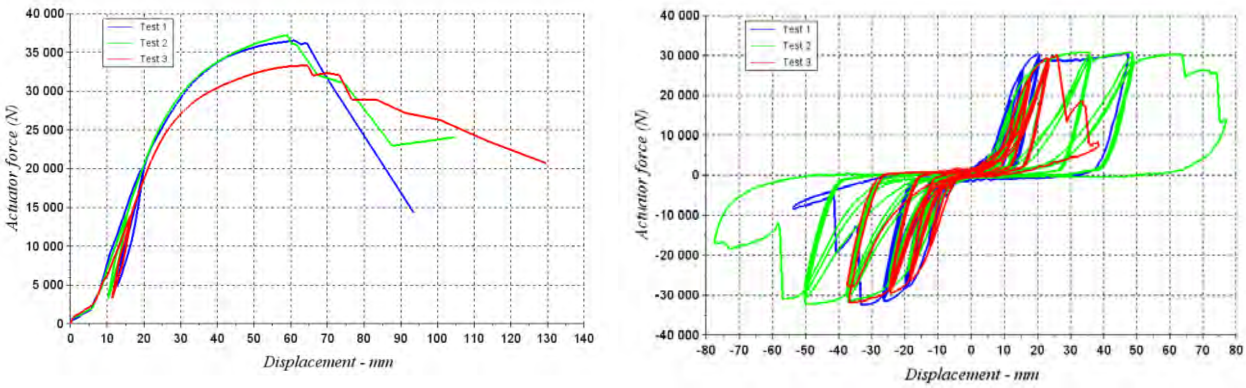


Figure 8 - Examples of (left) monotonic and (right) cyclic response of bracing frame for three tests.

4.2 Main characteristic determination

The tests enable the determination of the main characteristics of the bracing frame. Once more, the elastic stiffness, the maximal force and the equivalent damping will be confronted between the different scales for the whole bracing frame. Each test has been repeated three times to assess the measure uncertainties. The displacement δ_y corresponding to the beginning of the ductile behavior of the structure was estimated thanks to monotonic tests and used to fix the amplitudes of the cyclic tests. The equivalent damping was given for a cycle amplitude of δ_y. The full-scale frames broke for displacements between $1{,}5\delta_y$ and $2{,}5\delta_y$. The reduced scale frame broke for displacements between 2.5 δ_y and $4\delta_y$. This phenomenon may be explained by the relative mounting gaps that are much higher for reduced structure than full scale one. Table 5 and Table 6 show respectively the main parameters and the scale factors related to each scale.

Table 5 - Main parameters identified for bracing frame at different scale

	Full scale		1/2 reduced scale		1/3 reduced scale	
Number of tests	3		3		3	
Variable of interest x	Mean $\overline{x^{(F)}}$	CoV* (%)	Mean $\overline{x^{(R)}}$	CoV (%)	Mean $\overline{x^{(R)}}$	CoV (%)
Elastic stiffness K_e (kN/mm)	3.8	3.2	1.3	1.4	0.94	4.4
Strength F_u (kN)	35.7	6	10.2	8	4.16	15
Equivalent damping ν_{eq}*	5.2	9.4	5	19.3	4.5	17.9

Table 6 - Theoretical and experimental scale factors of main parameters of bracing frame

	1/2 scale			1/3 scale		
Characteristic x	Theoretical scale factor $\lambda_x^{(th)}$	Experimental scale factor $\overline{\lambda_x}^{(exp)}$	COV (%)	Theoretical scale factor $\lambda_x^{(th)}$	Experimental scale factor $\lambda_x^{(th)}$	COV (%)
Elastic stiffness K_e	2	3.15	3.5	3	4.04	5.4
Strength F_u	4	3.5	10	9	8.58	16.2
Equivalent damping ν_{eq}*	1	1.04	21.5	1	1.15	20.2

* The equivalent damping is given for a signal amplitude of δ_y

4.3 Distortion for wooden frames

Yet again, the equivalent damping is close to the same value for each scale, as intended by the dimensional analysis theory. The strength scale factor is closer than for the assemblies from the theoretical scale factor. During the conception of the bracing frame, the thickness of the steel plate was indeed increased to avoid flexural buckling and improve similitudes. Therefore, almost all the structure studied broke because of a ductile failure of bolts. The hypothesis of similitude theory was better fulfilled for the estimation of this parameter

Conversely, the experimental scale factor for elastic stiffness is very different of the theoretical one. This parameter is very sensitive to mounting gaps, local stiffness and friction that cannot be reduce in practice using similitude laws. Therefore, it may lead to a bad estimation of the maximal displacement for a full-scale structure if experiments are made on a reduced model.

Finally, we observe that the uncertainties tend to grow up when the mock-up scale decrease. Even if the similitude laws are perfectly respected, a test on a reduced model will lead to values that are more uncertain. This highlight the importance of evaluating uncertainties for our reduced model.

5. Methodology proposal

The sizing of a reduced mock-up must take into account experimental restrictions and structural representativeness. A too small structure will lead to inappropriate results as some geometrical parameter could not easily being scaled (thickness of metallic element, clearance…). Non-homogeneities of the material and non-linearity of assemblies lead to distortion of the response of the structure. However, too large structures will lead to the infeasibility to conduct experiments. That is why a compromise must be made.

Moreover, using scaled mock-up increases the uncertainties of the variable of interest studied which underlines the fact that these uncertainties must be evaluated to assess the acceptability of the experiment.

Based on our study, several steps are proposed to efficiently size a reduced mock-up.

- Identify the maximal capacity of the experimental means (dimension, load, maximal displacement etc…)
- Define the largest scale of the structure studied on which experiment are possible
- Identify the distortions of the reduced mock-up, the parameters that cannot be reduced properly due to practical limit.
- Check the failure mode of assemblies stay the same after reduction. Otherwise, distortions had to be made to ensure the preservation of the failure mode.
- Assess the uncertainties of the reduced scale structure. They will increase as the scale decreases.
- Assess the uncertainties due to distortions, non-linearity and non-homogeneity.

The failure mode of assemblies can be estimated quite easily thanks to norm and conception guideline (for instance, EN 1995-1-1 in Europe [20]. The uncertainties of the reduced scale structure should be given by the tolerance and the supplier. The most difficult aspect is to assess the uncertainties due to distortions and non-linearities that could be obtained by complex numerical simulations or experiments.

6. Conclusion and future works

In order to make experiments on large and complex structures with limited experimental means, the use of similitude laws is mostly compulsory. A careful attention has to be given during the sizing of reduced scale structure to be representative of the full-scale structure, especially in the case of timber buildings. A reduced mock-up of a section of a high-rise building was tested on a shaking table using dimensional analysis. Concrete blocks had to be added to ensure the representativeness of the structure. However, the failure mode of the structure was not the one expected because of the dimension reduction. Test on assemblies and on a bracing frames were conducted to observe the mechanical behaviour of wooden structure at different scale. The representativeness of assemblies are of the outmost importance to ensure the quality of the reduced structure, in terms of resistance and stiffness. The failure mode of assembly has to be the same at each scale. Nevertheless, a perfect similitude cannot be obtained due to nonlinear phenomena and experimental constraints and a compromise had to be found. Based on this study, a methodology to evaluate the sizing of reduced mock-ups was proposed.

In future works, it is planned to use numerical simulations to assess the influence of distortion and the main characteristic scale factors. Then bracing frame will be tested with an operational modal analysis with hammer to verify the dynamical representativeness of reduced scale mock-up.

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