Experimental full-scale testing of a multistory timber frame building concerning dynamic properties

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1.   Introduction

Since 2003 the Swiss codes demand to carry out an earthquake verification for building structures. The dynamic loads, that occur in a structure during an earthquake or dynamic excitation are not depending on the choice of a certain load, but on the dynamic response of the structure. Therefore, its dynamic behavior must be known, and the engineer usually chooses a fundamental period T_1 that he thinks fits best between various methods of calculation. One can obtain fundamental periods that differ a lot and so earthquake forces may differ to factor 5 or more for the same structure. In addition, especially in wood construction with wide spread material properties, the underestimation of material stiffness lead to higher forces.

The fundamental period, which is the longest period of a structure, is the time in which a building makes one free oscillation. The stiffness and the mass of the building are influencing the fundamental period. In fact, every building, as its never infinitely stiff, is oscillating even if people don't recognize. Interference of soil and building frequencies is crucial behavior while amplitudes get summed up.

As investigations have shown, timber frame shear walls are significantly stiffer than calculated with available means and codes. Dynamic properties of timber frame walls are difficult to predict, research in this domain is mandatory. Nevertheless, the engineer must choose one fundamental period for the building design. If its short and a period on the spectral plateau is chosen, high design forces will occur and a lot of anchorage pieces result, however if it is chosen long, seismic forces are little, its more economic, but this softness must be guaranteed once build.

Figure 1: Experimental plant with 4 story building and racks for cable tensioning system.

In Chamoson, Canton of Valais the building is erected and tested during summer 2019. On the floorplan it is 5,04 m x 3,86 m. The idea is to make a full-scale static and dynamic testing of a timber frame building during different stages. Therefore, the building is investigated during the erecting phase, but before in the laboratory to compare results from numerical analysis, laboratory results and the reality «as built».

There are two shorter walls in Y direction without openings and two longer walls in X direction with a window opening. According to the codes, the same stiffness for analysis must be used, because the shear length is identical.

Research has shown, that entire timber frame buildings [6], timber frame shear walls [5] and the staple connection between OSB and studs [2] have on one hand higher stiffness than calculations according to the code say, but on the other hand much higher stiffness in only very little excitation. Therefore, on-site measurement of fundamental period with ambient noise measurement (ANM) which is a non-destructive and relatively simple way to do the analysis will not give the same results than a free oscillation test. Deflection influences periods.

2.   Specimen and material properties

The walls consist of studs of 160mm in GL24h intermediate studs in C24 and a 15 mm OSB/3 on the outside. The connection between these two parts are staples 1,53/50 mm. This configuration provides accessibility during the erection phase from the inside. OSB are trimmed 20 mm on all sides. This prohibits friction between two adjacent panels or shoring a panel while it rotates under shear load. 20 walls were produced, that corresponds to 5 stories. Four walls are tested monotonous in the laboratory, to know the wall behavior for the full-scale building test and compare these results.
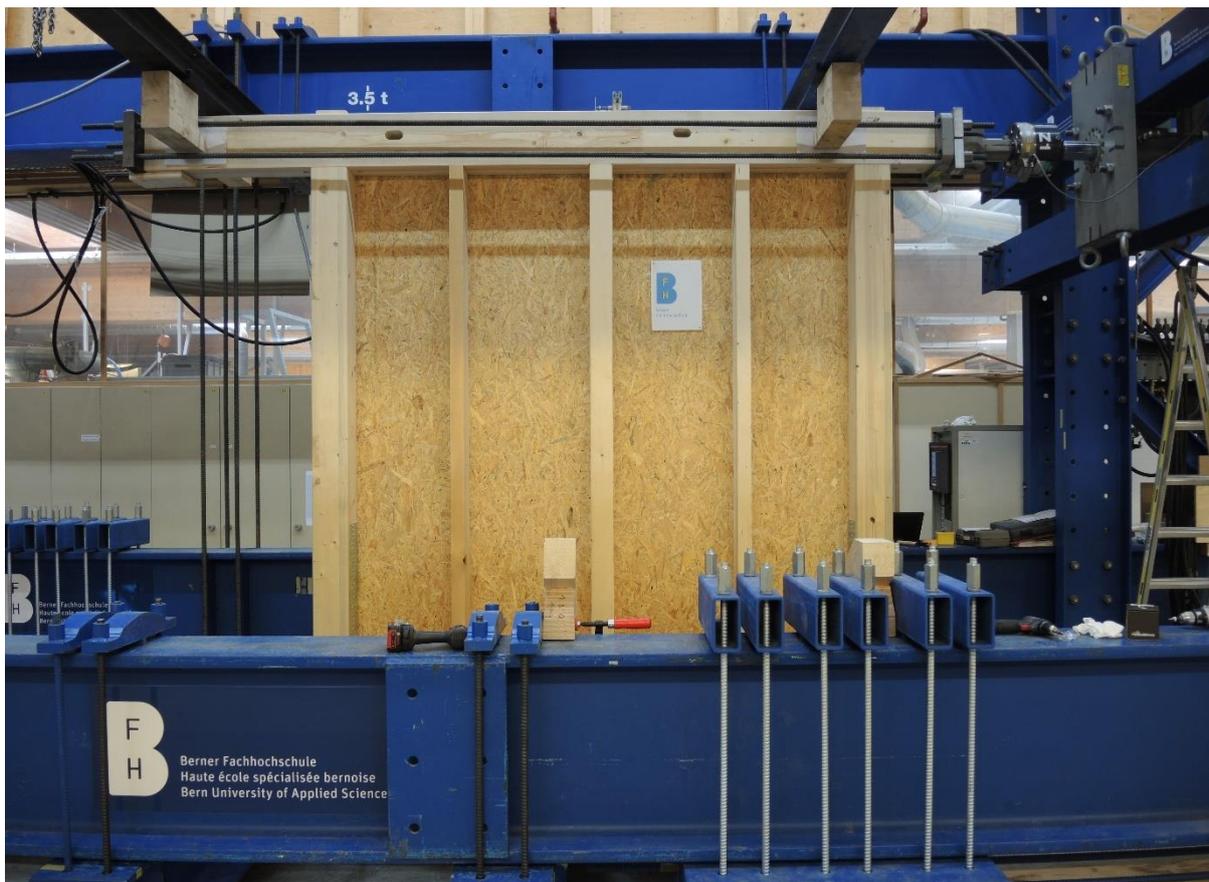
Figure 2: Timber frame shear wall "C2" during test in the laboratory at BUAS.

2.1. Glulam

Before wall assembly, every piece of glulam has been checked for density, Young's modulus and wood moisture content. The pieces are then sorted by density and designed at the right place for the wall assembly. Pieces with highest densities are set in the ground floor and lower densities in the top stories. The knowledge of Youngs modulus for each piece allows a precise numerical analysis.

Figure 3 shows the density results after sorting.
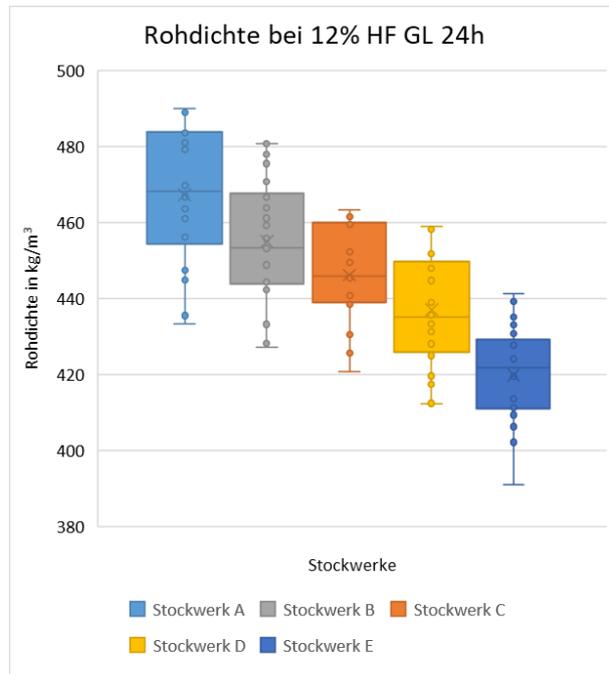
Figure 3: Density of glulam pieces corrected to 12% wood moisture content. Boxplot groups according to the story belonging.

2.2. OSB

OSB/3 15mm are checked for density, but no sorting is done. However, some specimens are set aside to investigate the shear modulus in grain direction and perpendicular to it. All boards used for the wall sheeting belong to one production cycle. Material properties should therefore be relatively homogeneous. The panels are size of 1,25 m x 2,70 m.

2.3. Staples

Properties of staples are determined by a preliminary analysis in this and other projects at Bern University of Applied Sciences. As a result, the slip modulus of staples is higher, than building codes predict. Especially in little excitation, the stiffness of these connections is significantly higher. Among other things, friction between OSB and studs may contribute to this increased stiffness.

For the tests to follow, influence on stiffness after several loading cycles must be assured. In other words, one must be sure that staple connections and so the walls have the same stiffness during the different testing stages, to compare the displacements and periods obtained. Results show, that 200 preloading cycles to the dimensioning value for staples ($F_{R,d}$ = 0,34 kN/staple) has no influence of on slip modulus of the connection. Therefore, most of the tests are scaled to 67% of this force level with intention to not plastify or damage this connection in advance.

Influence of humidity to the stiffness of staple connections must also be considered. Tests were done to compare different full-scale test results. Temperature and air humidity are constantly logged on the building site and wood moisture content is checked after every testing day.
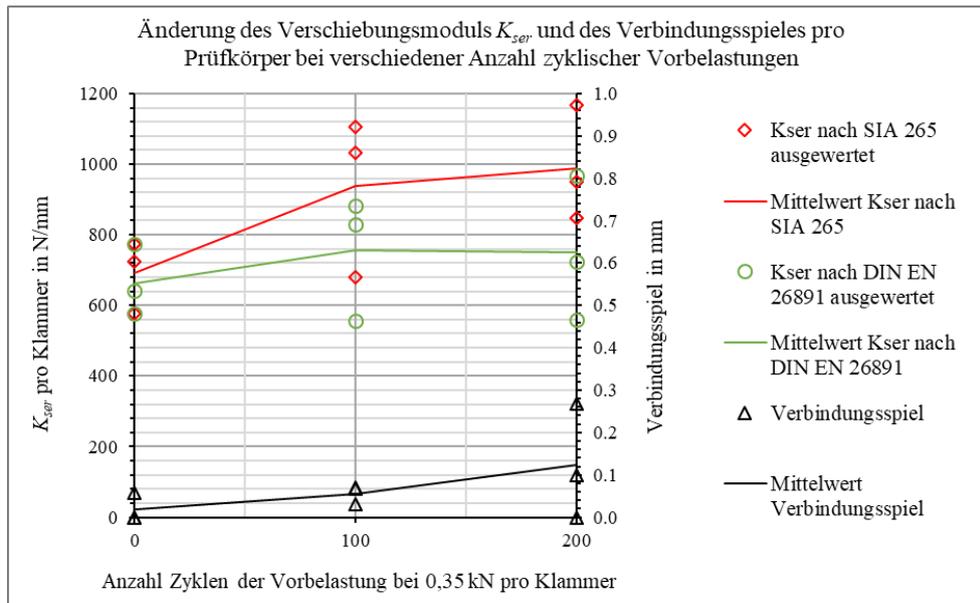
Figure 4: Variation of slip modulus of the stapled connection between OSB and glulam for different preloading situations. Depending on the evaluation method, slip modulus doesn't change or increases little [2].

2.4. Anchorage and story connection

Anchorage of vertical forces are executed by hold-downs. Between the foundation and the ground floor, there is a special steel anchorage piece, because of high tension forces of 550 kN. The connection of vertical forces between two stories is made with hold-downs type WHT740 XXL and threaded steel bars M24. All steel pieces are connected to the wood by screws LBS 5x70 predrilled with 3 mm. Main advantage is that there are only few different connector properties that must be known for the numerical simulation.

The shear connection from ground floor to foundation and between two stacked walls are done with classical wood screws 8x220 that go either in wood or in concrete (predrilled).

Figure 5: Action and reaction forces for two wall setups. On the left side: X-wall, right side: Y-wall.

2.5. Wall specimen

Each wall is preloaded in a cyclic test setup in the testing frame of the laboratory at Bern University of Applied Sciences in Biel. Three different force levels are defined, to 24%, 50% and 67% of the design value for staples by code SIA 265/1. These values correspond to the design value of exposure for staples by the annual wind, the wind with ten-year return period and the wind of fifty-year return period.

For calculation according to the code the walls in Y- and X-direction have the same stiffness, because sheeting at openings is not considered. X-walls have a shear length of 2*1,25 m = 2,5 m and Y-walls a shear length of 2,5 m at one piece.

The graph below shows significant differences in stiffness between the X- and the Y- walls, but also stiffness variation due to the amplitude of loading.
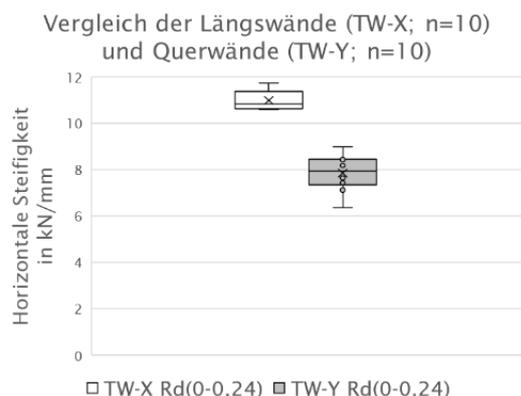
Figure 6: Comparison of horizontal stiffness between X- and Y-walls.
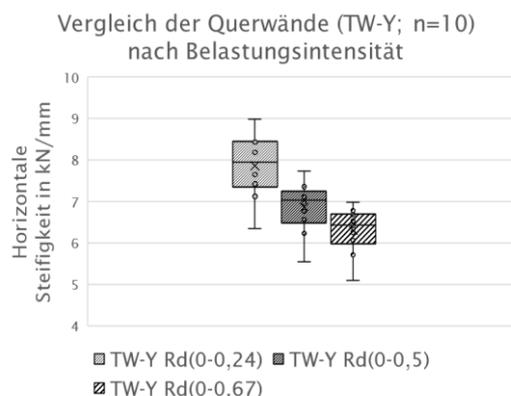
Figure 7: Comparison of horizontal stiffness for Y-walls with different loading intensities.

2.1. Floor slab

Floor slab composition is a wood beam construction of massive wood with a 25 mm OSB/3 on top for diaphragm effect. The panel is stapled to the beams and the joint between the panels is 20 mm.

Tension forces of the rope system are anchored with horizontal fixed hold-downs directly to the floor. In the middle of the floor there is an opening to access the different stories. It contains a little stair-case which is completely independent of the rest of the structure over the whole height of 10,80 m with enough space around, to let the building move.

Figure 8: Anchorage on floor slab to pull on the building.

2.2. Foundation

The foundation is a concrete plate of size 7 m x 10 m and 40-45cm thick. It is designed, to resist the pushover test of the building. Anchorage pieces are already set in place before pouring the concrete.

Figure 9: Pouring the concrete of the foundation. Anchorage pieces are already set.

2.3. Calculation model

The calculation is based on current codes with applying a ductile dimensioning to the structure. Thus, there must be a mechanism installed called hierarchy of resistances. Let's imagine a chain, and the chain will deform or break at the weakest chain link. Therefore, all other chain links must be stronger, to be sure, that the determined link to fail is the link which fails first and can dissipate the energy. In timber frame construction the weakest link, by the way highly ductile, can be attributed to the staple connection. But then all other parts, like the resistance of OSB, resistance of anchorage must be over dimensioned, thus higher.

The estimation of the fundamental period can be done by simple formulas as SIA 261.39 and leads mostly to short periods on the plateau of the soil acceleration response spectrum. Or bar models with replacement stiffness can be used to determine the answer of the building, which leads mostly to longer periods because of underestimation of material stiffness.

Numerical simulation for stiffness is done by using material properties from the building codes and the measured material properties to refine the calculation model where needed. Every wall, and every piece of wood or concrete that is set in place was measured with the balance shown in Figure 11 to precisely know the masses for the simulation. The measurements on site are compared with an engineer's approach of mass estimation for load assumptions and for a mass determination with a complete 3D model.

2.4. Mass

In order to have some realistic building masses for dead-loads, 8 prefabricated concrete blocks are added on each floor slab. This is a mass of about 1,25 kN/m^2 that corresponds to screed and floor composition.

The structural dynamic behavior depends on stiffness and mass. A lot of energy is set in the wright acquisition of stiffness, but also masses must to be known for a precise analysis.

Figure 10: Prefabricated concrete blocks to simulate dead-load in a building.

Figure 11: Balance suspended on crane to weigh all pieces set in place.

3.   Testing phase and measurement equipment

Figure 12: Evolution of the test building. During the erecting phase four different buildings were tested.

The testing phase began with material properties in January 2019. Then walls got assembled. After wall assembly they were tested in March at the laboratory.

In May the erection at the building site began. The tests were carried out after each added story. So, in fact 4 buildings were tested. For each building, first the Ambient Vibrations were recorded with accelerometers. Then the rope tensioning system was installed and tensioned. Displacement of free oscillations are recorded inside with displacement transducers which can measure the distance between the free-standing staircase and the floor slab on top of the building. The floor slab has an opening in the center of the building. From the outside an optical measurement system records the displacements at several positions on the building at once. This Digital Image Correlation (DIC) system allows to determine the deformations in and out of plane at each recorded surface. Hence, mode shape analysis, static and dynamic behavior of the building can be extracted. Due to high picture sampling rates frequency analysis is also possible.

However, frequency analysis will mainly be extracted from the accelerometers.

At the foundation anchorage pieces strain gauges were installed, primary to observe spatial effects, but it came out, that building frequency analysis is also possible with these devices, even if the anchorage pieces work only in tension.

The 4-storey building is exposed to free oscillations that exceed nearly by factor two the earthquake of the code for this building on this site.

Measurement equipment on site was all supplied by a solar system, because electrical energy was not accessible on site.
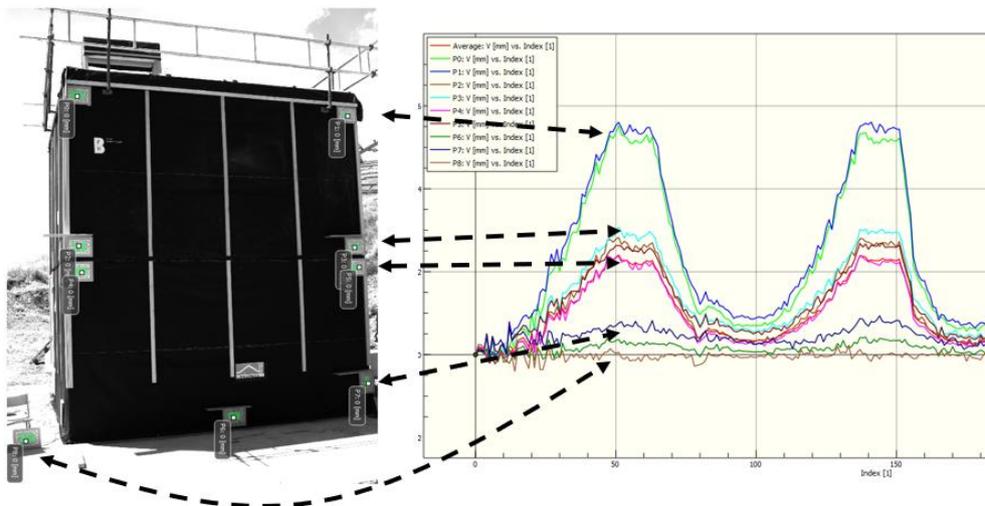
Figure 13: Symbolic DIC result for the two-story building in X direction. On the right graph on the ordinate is the horizontal relative displacement in X and the abscissae represents the pictures. The rope is tensioned several times on the building, before releasing the rope system.

At the end, a full-scale pushover test is executed as a monotonic test in field. Tension forces are so high, that the force and displacement graph for the static-nonlinear system is obtained to extract the yielding point of plastic deformation.

4. Investigation and objectives

The following questions should be answered at the end of the project:
– How can the fundamental period be determined for timber frame buildings?
– Is there a significant difference between the fundamental periods in X- and Y-direction of the building?
– What is the relationship of frequency between ANM and test by free oscillations?
– What is the relationship of damping between ANM and test by free oscillations?
– Are there spatial effects in the load bearing structure by neighboring walls?
– What are the mode shapes?
– Composition of deformation portions in timber frame shear walls and buildings?
– The torsional influence in a building with "perfect" symmetry?

5. Acknowledgements

6. Literature

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