EXPERIMENTAL ASSESSMENT OF THE POST-AND-PLANK WALLS BEHAVIOUR

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Abstract. Knowledge about the behaviour of historic timber structures is essential for the preservation of immovable cultural heritage. One such structure is the post-and-plank wall, which is present in different regions in the Republic of Bulgaria. An experimental study was conducted to evaluate the structural behaviour of the post-and-plank walls typical of the region around the town of Kotel. The experimental specimen was built and tested under a combination of vertical and horizontal monotonic loads. Two methods were used for the measurements – by displacement transducers and Digital Image Correlation (DIC). The wall was analysed in terms of lateral load, lateral displacement, sliding of wall elements and failure mode. Results show that the mean percentage difference between classical measurements and DIC measurements observed is less than 3%.

Keywords: post-and-plank wall, digital image correlation, full-field displacement.

1. INTRODUCTION

It is well known that a timber is one of the oldest building materials used by humankind. Design and execution of timber structures followed different approaches in the past than nowadays. Experts and non-experts are asking themselves about the stability and load bearing capacity of the old structures.

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What is more, a big part of the historic buildings is declared as immovable cultural heritage and should be protected according to the national and international legislation. Ensuring earthquake resistance of buildings is a main task in seismic areas.

Vernacular typologies are various and reflect the local weather and topographical conditions, crafts, tectonic activity, etc. One such typology in the Republic of Bulgaria is the post-and-plank timber structure which can be found in mountainous areas with abundance of deciduous forests. There are differences in each region and the following research is concentrated on the region around the town of Kotel. The residential buildings there are mostly two-storey. The ground floor has between one and three timber facades and the second floor is all made of timber. Floor and roof structures are also made of timber. These walls have been previously studied and more detailed description can be found in [1–2].

To analyse the structures of those historic buildings and reduce the interventions to a minimum, the structural engineers should know the properties of the materials, the stiffness of the joints and the bracing of the global structure.

Laboratory experiments remain the most reliable methods to evaluate real behaviour of timber walls. To measure full displacement fields by means of classical measuring devices, such as displacement transducers, is a challenging task. The full-field optical technique based on the Digital Image Correlation (DIC) is a tool gaining popularity as a way to capture more detailed information about displacement and deformation fields of objects [3–4]. The DIC method is widely utilized today in experimental mechanics, because it can be used for almost all kinds of tested material (wood, metal, ceramics, polymers, natural tissues), at a huge scale of digital images (from micrometres to tens of meters) and relatively acceptable initial costs. There are various studies applying DIC for examination of wood deformation characteristics at different loadings: compression [5], tension [5–6] and bending [7]. All these articles illustrate the potential of DIC method for studies in the mechanics of wood materials. Therefore, utilization of DIC method to acquire full field on displacements of timber walls can be recommended.

The aim of this paper is to understand and characterise the behaviour of post-and-plank timber structures by employing an effective combination of the classical method with displacement transducers and the DIC technique.

2. EXPERIMENTAL PROGRAM

2.1. Specimen description

The most common wood species for timber structures in the region around Kotel was oak. Taking samples from real buildings was impossible and would have included many imperfections. Massive oak timber with the size of the posts and the beams was also almost impossible to find. It was decided to produce oak glulam beams and posts for the experiments in a carpentry workshop. Kiln-dried planks with thickness of about 30 mm were used and all the sizes of the elements were divisible by 30 mm.

The dimensions of the specimen were determined from measurements of real structures, because the size effect has a big influence on the load-bearing behaviour of the timber structures. The wall has 3 vertical posts, 2 horizontal beams and 14 planks. The dimension of the test specimen is equal to 1.88×2.00 m, which corresponds to 3.76 m^2. Along the height of the wall, the width of the planks is different and varies between 220–295 mm. Figure 1 shows the details of the test specimen.

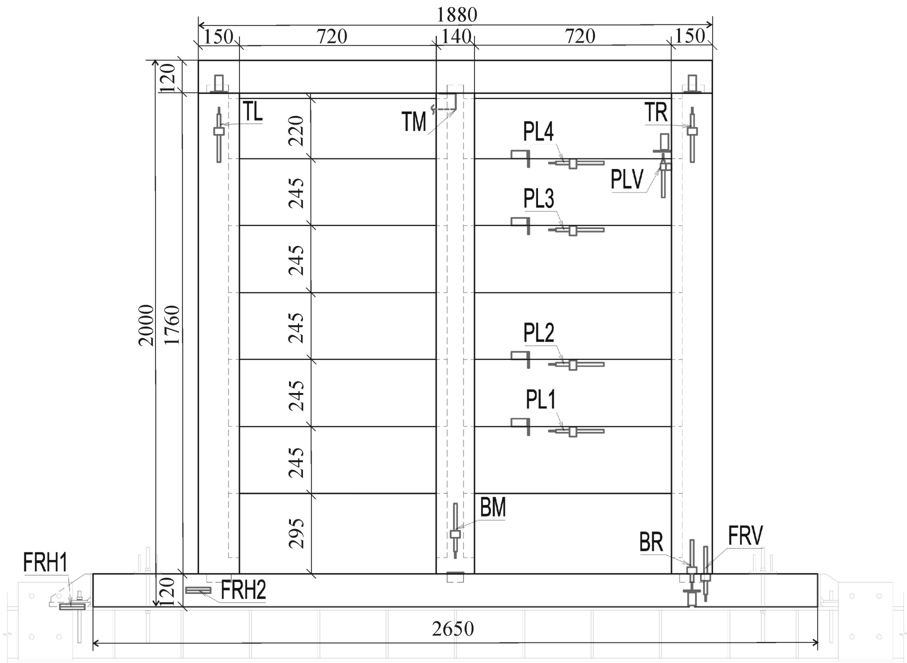


Fig. 1. Details of the tested wall

The timber elements for the experiments were conditioned in a controlled environment with temperature $(20 \pm 2)\,^{\circ}\mathrm{C}$ and relative humidity $(65 \pm 5)\,\%$ for four months in conformity with [8].

2.2. Test set-up

The wall specimen was tested under constant vertical and monotonic horizontal loads at the Structural Engineering Laboratory of the University of Architecture, Civil Engineering and Geodesy. The wall was mounted in a vertical position on the loading frame. The bottom beam of the specimen was restrained in vertical and horizontal direction, Fig. 2. The out-of-plane deformations were limited by two longitudinal steel beams in contact with the top beam of the wall. Polytetraflouroethylene (PTEF) plates were mounted between the steel and timber beams to eliminate the friction forces and allow free horizontal in-plane displacements of the wall. Two actuators were used to apply the gravity loading and the horizontal displacements. Reaction forces of the vertical actuator were transmitted to a roller block. The roller block was sliding on a longitudinal beam anchored to the reaction floor. This guaranteed that the vertical force was kept constant during the experiment. The forces and displacements were manually controlled by hand hydraulic pumps.

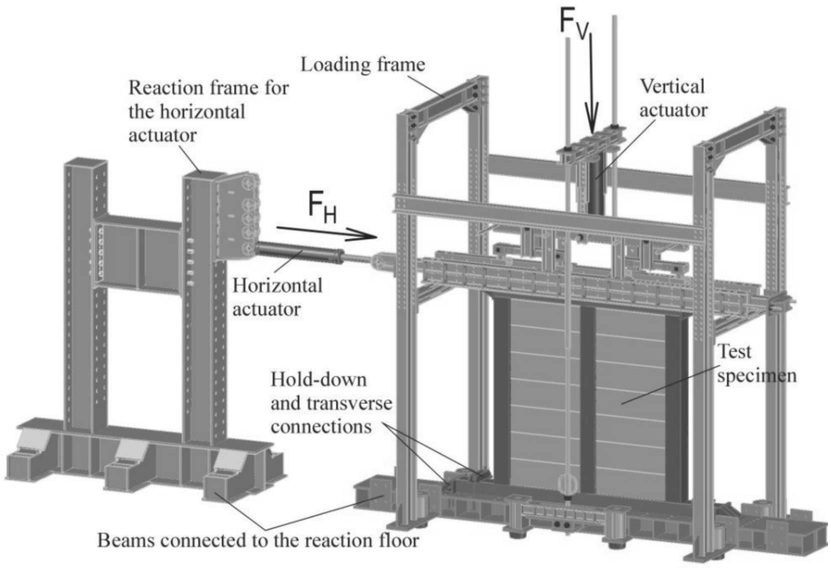
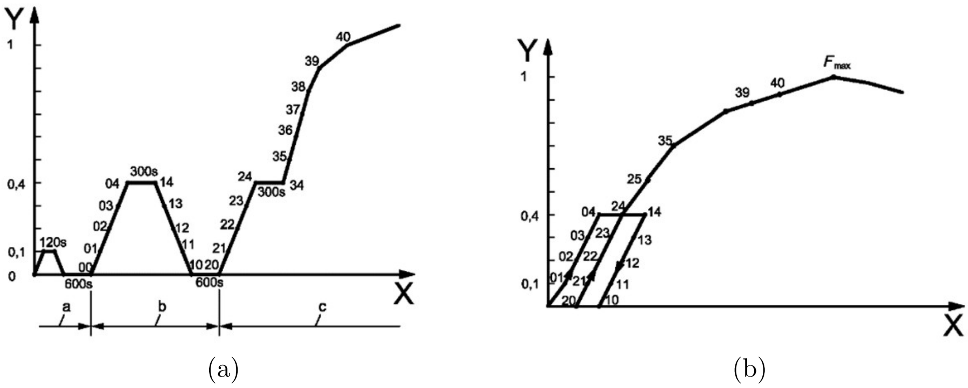


Fig. 2. Test set-up

The vertical load was calculated for a wall on the ground floor of a two-storey house based on real measurements of houses. The vertical loading is the gravity load which is acting on the structure. It is applied at the beginning of the test before the horizontal displacements and stays constant during the whole experiment. A seismic combination according to [9] was considered. The loading was divided into two stages. At first, the vertical load of 13.3 kN/m was applied and after that a horizontal force of 8.31 kN. The wall was unloaded and the main loading until failure was carried out. The loading protocol and test set-up were in conformity with ISO 21581 [8]. The calculation is described in detail in [2], based on the test procedure in [8] (Fig. 3). To define a loading protocol, a preliminary calculation of the ultimate lateral force was necessary. Following the requirements of ISO 21581-2010 standard, preliminary test was conducted to get initial data and F_{max}. Then a test protocol was developed using F_{max}, maximum force from experiment, and $F_{\text{max,est}}$, maximum force estimated from numerical model.

The loading rate was equal to 0.05 mm/s and remained constant during the whole experiment. The force was measured as a reaction of panel based on the hydraulic pressure of load cylinder. Horizontal displacements were measured by TM inductive transducer attached at the centre of wall. The sampling rate was chosen to be 2 Hz, taking into account the fact that the sampling rate of camera was 1 Hz and the experiment is static (monotonic) test.



(a) (b)

Fig. 3. Test procedure – static (monotonic) test. Source ISO 21581-2010 [8]: (a) lateral load Y [N] versus time X [s]; (b) typical lateral load Y [N] versus deformation X [mm]

2.3. Data acquisition methods

Experimental data was acquired by displacement transducers and DIC. The combination of these two methods allowed to control the accuracy and to attain a detailed picture of the deformations of the wall. The facade side of the wall was measured with the DIC method and the displacement transducers were mounted on the back of the wall, Fig. 1.

A mean percentage difference is defined to compare the displacement resultants obtained from the displacement transducers and the DIC approach:

$$C\% = \frac{|D_{DT} - D_{DIC}|}{D_{DT}} \times 100\%, \tag{1}$$

where D_{DT} is the displacement by displacement transducers and D_{DIC} is the displacement with DIC measurement.

2.3.1. Displacement transducers

Thirteen displacement transducers were mounted on the wall. Their positions were determined in accordance with ISO 21581 [8] and additional places where the largest displacements were expected, Fig. 1. The displacements were recorded at every 0.5 sec.

2.3.2. Digital image correlation method

The basic principle of the DIC method is finding the correlation between individual pixels of two digital images [3–4]. A random pattern is applied on the observed surface and its change is tracked through the reference and the deformed images. The reference image is divided into "subsets" that represent a square matrix of pixels. The relative difference between coordinates of the subset before deformation and after deformation corresponds to an absolute displacement of these points on the deformed object surface.

The DIC system used in this research consists of the following elements: one digital recording unit (camera with a CMOS sensor), a lens, a tripod, a source of white diffuse light, a computer unit with adequate computing power and software for the calculation of correlation coefficients, displacements and strains, Fig. 4. A camera Sony Alpha a6000 is used with CMOS sensor (23.5 × 15.6) mm possessing a maximum resolution of 6000 × 4000 pixels and a frame rate up to 11 images per second. The lens focal length is 35 mm. The camera optical axis was adjusted to be orthogonal to the studied surfaces, which are illuminated by white light sources. The distance from the camera

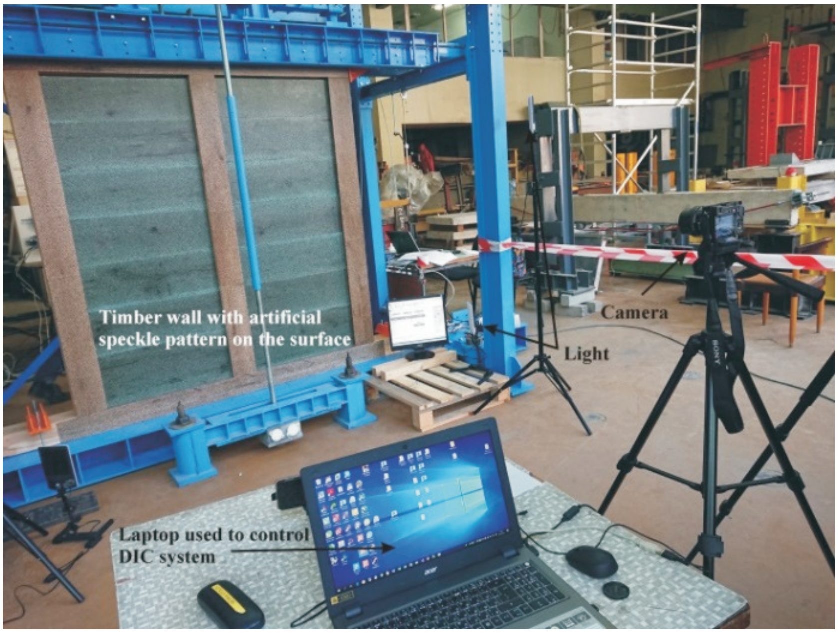


Fig. 4. DIC set-up

to the monitoring surface is kept invariant during the experiment. The camera was positioned at a distance of 3 m from the specimen.

Figure 4 shows a picture of the DIC test set-up. On the front surface of the wall specimen a random pattern with good contrast was created. It was applied by a mat adhesive foil. The method of generating random patterns is explained in detail in previous publications [10–11]. The software used to analyse and display the resulting 2D full displacement fields was developed by the authors within "Microsoft Visual C++" environment.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 presents the load–displacement relationship obtained by the two methods. The DIC results are calculated at intervals of 2 seconds and this affects the accuracy of some points. The values of the differences between classical measurements and DIC measurements were calculated by using equation (1). The mean percentage difference is less than 3%.

Figure 6(a) shows the unloaded state and Fig. 6(b) – the final deformed state of the specimen. The results for the horizontal sliding of the planks versus the horizontal displacement of the wall are shown in Fig. 7.

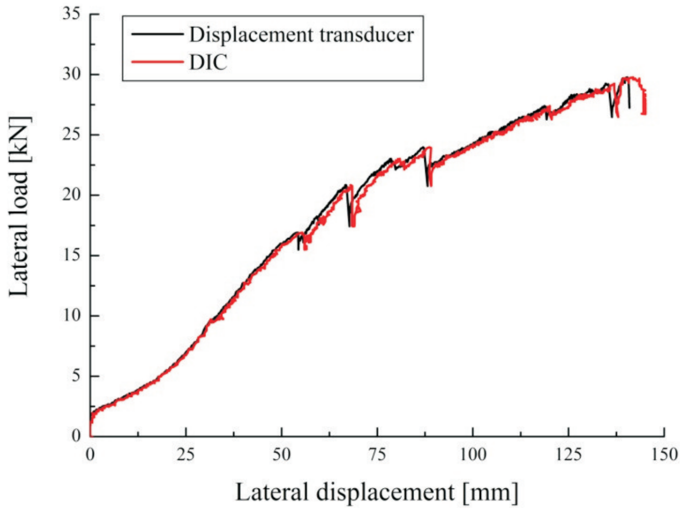


Fig. 5. Load–displacement relationship

The measurements are relative, i.e. the displacements are between two planks one above the other as shown in Fig. 1. The DIC results are also calculated relatively for the purpose of comparison. Overall, the displacement curves coincide with very well throughout the test. The largest deviation between measurements occurs by all transducers near the end of the test, just prior to failure. Probably small displacements in this area explain discrepancies between the measurements.

The behaviour of the specimen during the loading can be tracked in detail by using the DIC measurement data. The DIC system illustrates the results in form of displacement vectors and isolines, Fig. 8. The isolines are at intervals of 2 mm.

The grid is at intervals of 20 mm and the vectors scales are 1:1. The white zone in the middle cannot be processed because it is hidden by the steel rod of the loading frame. The top left corner is also hidden by the loading frame at the end of the experiment (Fig. 6). Movements as a solid body into each of the horizontal planks are encoded by colour variations. Thus, isolines seemed to clearly characterize the difference of behaviour in the planks. It should be noted that the planks were not bonded. That is why the number of different displacement regions is equal to the number of planks. As can also be seen from the displacement vectors, the bottom board has the least horizontal displacement and the top board has the largest horizontal displacement. In the horizontal direction, a maximum displacement (approximate 15 mm) at

(a) (b)

Fig. 6. Images in: (a) unloaded states; (b) deformed states

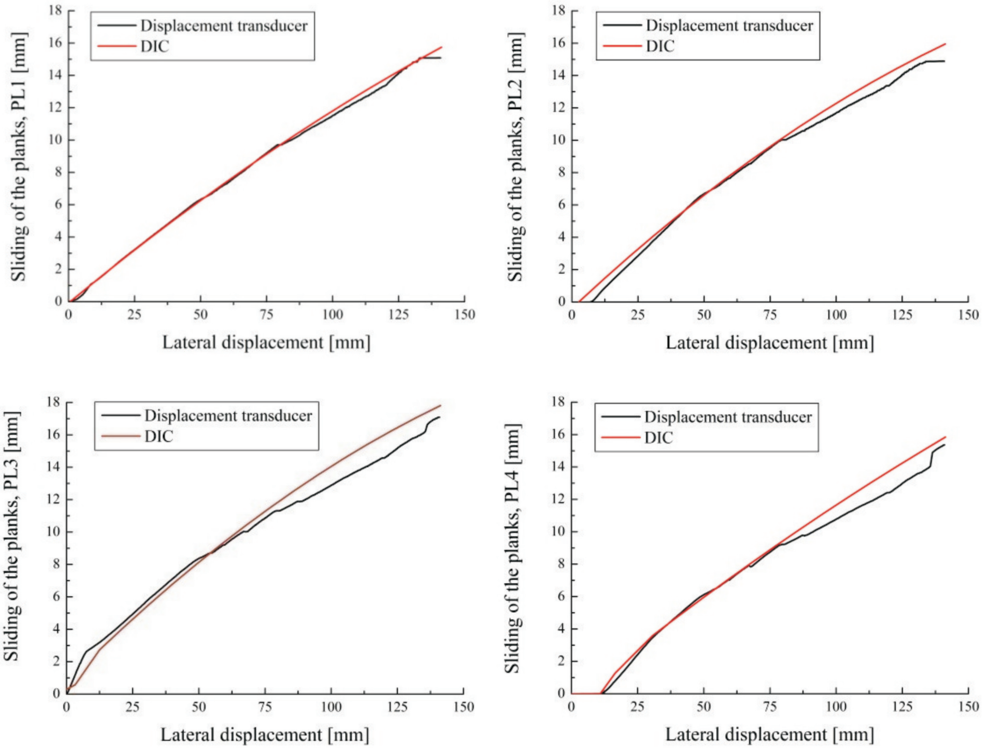


Fig. 7. Horizontal sliding of the planks. The positions of the displacement transducers are shown in Fig. 1

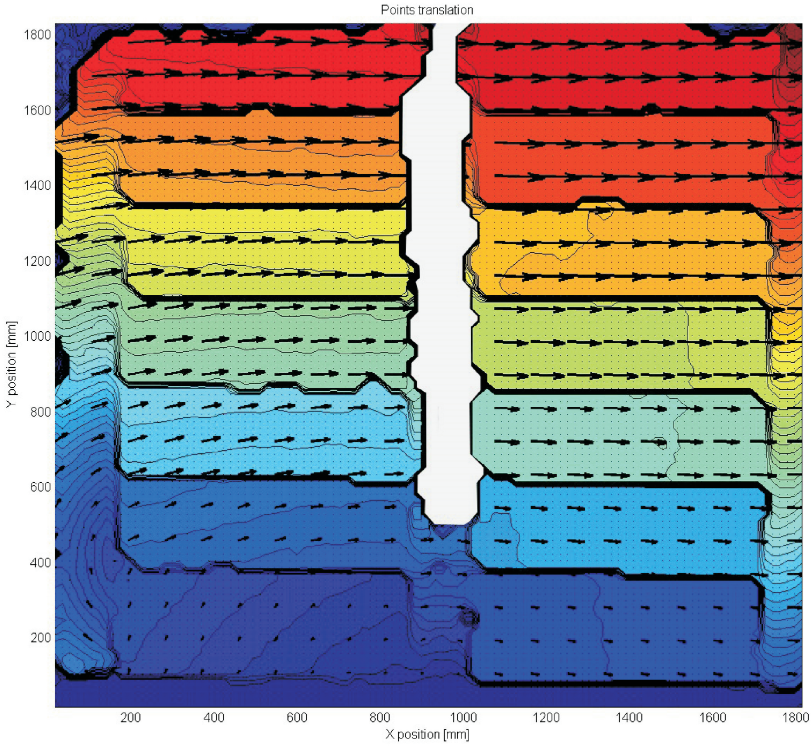


Fig. 8. Displacement field in the XY-plane obtained with DIC

the right top of the wall was observed. There were not only horizontal displacements but also vertical displacements (see the vector slope in Fig. 8). A maximum displacement at the left post was observed. The post was moved upwards.

4. CONCLUSIONS

In this article, the behaviour of post-and-plank wall specimen made of oak was experimentally studied. The wall was tested under a combination of constant vertical and monotonic horizontal loads. Lateral load, lateral displacement and sliding of wall elements were analysed. Displacement transducer and digital image correlation were used for the measurements. The DIC system does not aim to replace the assessment of the complex interactions in post-and-plank wall loads with standard methods. It rather offers additional information on full-field displacements in the case of large specimens. Lastly, the maximum difference between classical measurements and DIC measurements was calculated.

The present article is a first step to understand the behaviour of the post-and-plank walls. Further studies should be conducted at a model level by means of Finite Element Method reproducing the experimental procedure.

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