Vision-based monitoring data to inform new assessment techniques for tunnelling-induced damage in historic masonry buildings

Report describing activities supported by 2020 IStructE Research Award

UK team: University of Oxford (Sinan Acikgoz [sinan.acikgoz@eng.ox.ac.uk] , Harvey Burd, Burcu Gulen, Yiyan Liu), ARUP (Michael Devriendt, Ben Gilson). *Turkey team:* Izmir Institute of Technology (Deniz Dalgic), Istanbul Technical University (Alper Ilki), Fibrobeton (Muhammet Marasli)

Executive Summary:

Current procedures to assess the risk of excavation-induced damage to masonry buildings ignore key aspects of the problem (e.g., the influence of building weight, slab type and openings in the facades); they also lack experimental validation. To quantify the influence of these aspects on structural damage, we subjected four half-scale brick masonry buildings to settlements. We documented the structural response using video cameras and measured displacements using digital image correlation. Observations of building behaviour provided new insight into the problem; tests demonstrate how increased building weight increases compliance to applied settlements, how stiff concrete slabs prevent the propagation of building damage to upper floors and how openings significantly increase the strain demands experienced by structural components. In our ongoing research, we are using this comprehensive dataset to evaluate (and where necessary improve) the key indicators that are calculated from displacement measurements to quantify damage in buildings. Data and publications arising from this research will be made available to the public via the Oxford Research Archive.

1. Description of tests and observations

The experiments were conducted at Fibrobeton's factory site in Duzce, Turkey between December 2020 and March 2021. The setup used to subject buildings to settlements featured two parallel steel beams. Each steel beam was supported at its far corner and mid-span via metallic hinges, while a screw jack was used to subject settlements up to 90mm at the near corner (see Figure 1). This setup was designed to produce settlement profiles underneath the building that are similar to those induced by excavations. Four two-storey building models (referred to as specimens) were constructed and subjected to the same settlements. These buildings featured the same clay brick and cement mortar materials, laid in a single-brick thick English bond pattern. To ensure similarity to full-scale buildings, kentledge was placed on the first and second floors. Specimens differed from one another with respect to (i) the weight they carry (regular loading, double regular loading or with additional loads on building ground floor window sills), (ii) the amount of window openings they have (3 or 5 window openings per floor), and (iii) their floor structure (cast in-situ reinforced concrete (RC) slab or beams supported by metallic joists).

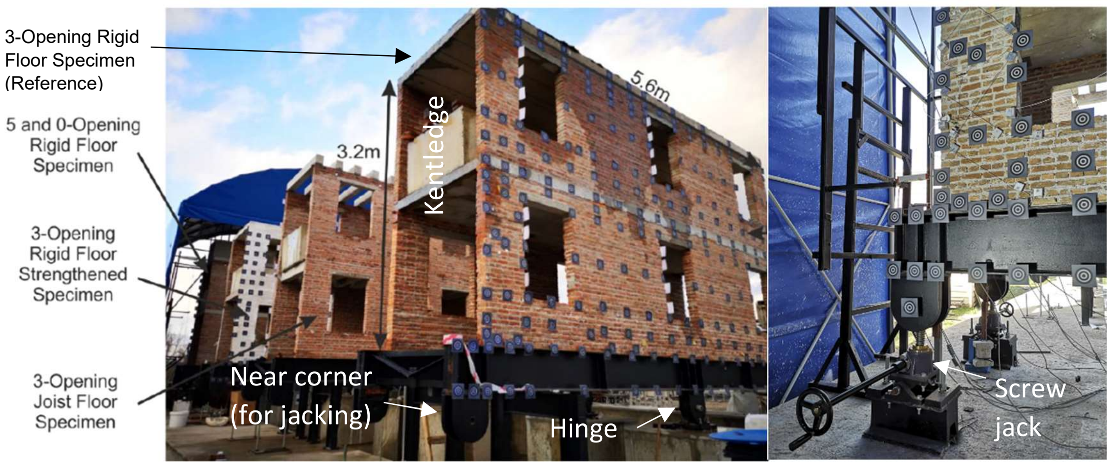

Figure 1 – The experimental setup and specimens.

Figure 2 illustrates how these individual aspects influenced the structural damage. The most important findings from the tests are summarised below:

- The reference specimen has 3 window openings per floor and an RC slab (see Figure 2a). When subjected to settlements under regular loading, a gap appeared between the building and the steel beam at the far and near corners (see Figure 2b). The building was able to support its own weight by redistributing the loads and rotating as a rigid body while avoiding any distortions. When additional kentledge was placed at the ground floor window sills of the same building (Figure 2c), it could no longer support its own weight with a gap opening underneath when subjected to settlements. Gaps closed, leading to geometric distortions and damage. Locations of damage are highlighted in Figure 2d; cracks up to 15mm were observed around first floor window corners and slender pier elements for a beam tip settlement of 40mm. This finding highlights the need to account for weight influence in assessments, increased weight can cause the structure to become more compliant and closely follow the induced settlement profile.
- Under regular loading, the 5-opening specimen (with RC slab) experienced noteworthy damage, distributed across different locations of the facade. These locations are shown in Figure 2e. This is in contrast to the 3-opening specimen, which did not experience damage under the same loads and similar settlement profiles. Damage around the top side of the edge pier is shown in Figure 2f. These comparisons highlight the need to account for the influence of openings in assessments, as openings strongly influences the concentration of stresses and failure patterns under the influence of settlements.
- Under regular loading, the 3-opening specimen with joist floors experienced a large crack extending across the full height of the building (Figure 2g). This type of damage was different from those observed in other specimens which featured RC slabs that prevented crack propagation to the second floor of the buildings. This specimen highlighted the need to consider in detail the stiffness of floor elements while conducting assessments.

2. Monitoring, data processing and key indicator evaluation

Paper targets glued on the building façades and the steel beam (see Figure 2) were tracked using digital image correlation techniques to determine displacements. These displacements were verified by cross-comparisons between overlapping measurements from different cameras and independent measurements from different systems (i.e., fibre optic strain sensors and linear variable displacement transducers). The validated displacement data was used to achieve several objectives:

- To visualise absolute displacements across the whole façade. This enabled an improved understanding of structural response (see Figure 3, which shows the vertical displacements induced to the steel beam and experienced by the reference specimen, alongside visual descriptions of the deformed state of the building). This data will later be used to evaluate numerical model predictions.
- To measure crack opening. By measuring the relative displacements between targets on opposite sides of a crack, crack opening can be reliably estimated (see Figure 4, which shows the crack width time history of the reference specimen, alongside the crack location and width at a specific settlement). This allows us to quantify the number and width of cracks and categorize the observed damage according to well-established criteria.
- To estimate strains experienced by individual building components. New procedures were developed to estimate the strains experienced by different parts of the structure (see Figure 5, which shows the calculated strains for the reference specimen). This procedure idealises piers as beam elements and spandrels as shear-deformable quadrilateral elements. These idealisations allow strain estimation in each element directly from displacements and can be used to evaluate how strain estimations correlate with crack widths. Since empirical strain and crack width

correlations are commonly used in engineering practice, this data will provide a useful evaluation of existing procedures.

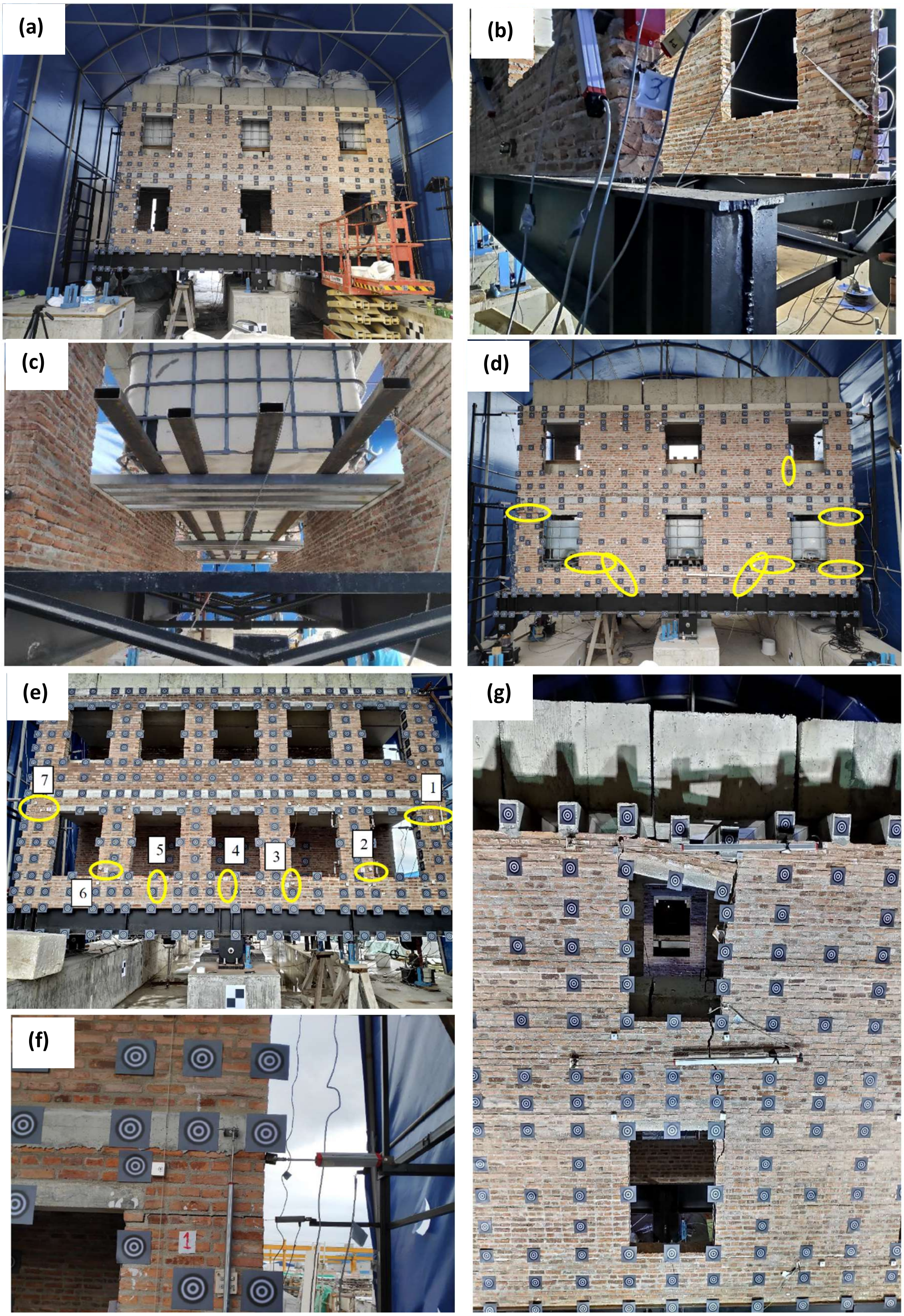

Figure 2 – Photographs demonstrating specimens and the damage they experienced during tests

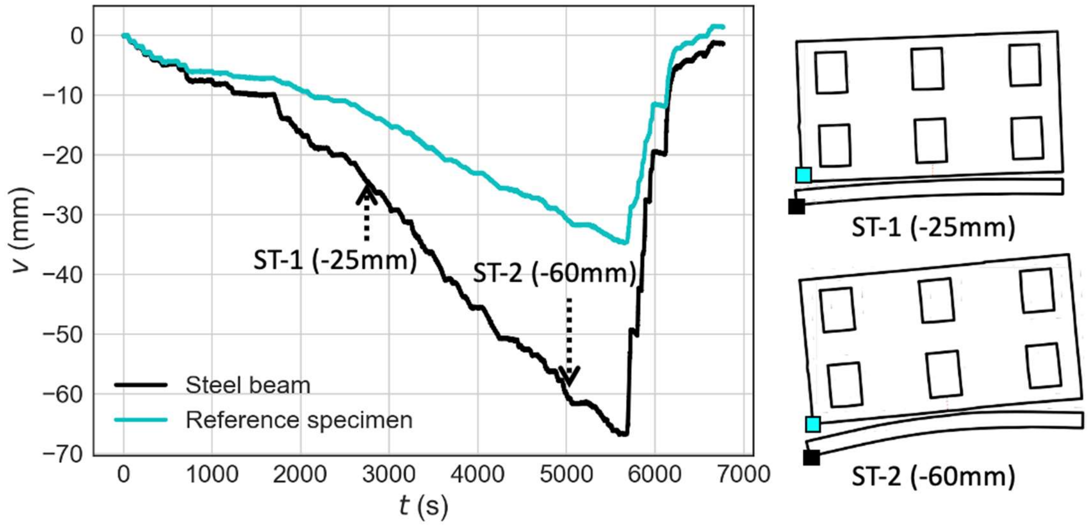

Figure 3 – (left) Vertical displacements induced to the steel beam and experienced by the reference specimen, **(right)** alongside visual descriptions of the deformed state of the building

- To evaluate key indicators that are used to quantify building damage. In engineering practice, only a few displacement measurements are conducted across the whole structure and building damage is estimated by processing these displacements. In particular, key indicators of damage, such as maximum principal strain of a beam model equivalent to the building, are calculated and compared against limiting tensile strain criteria. Over the last three decades, many simple key indicators have been proposed, including building tilt, shear distortion and horizontal strain. By using the detailed crack data, and building component strain estimators, the validity of these key indicator measures will be evaluated (see Figure 6 for an indicative example).

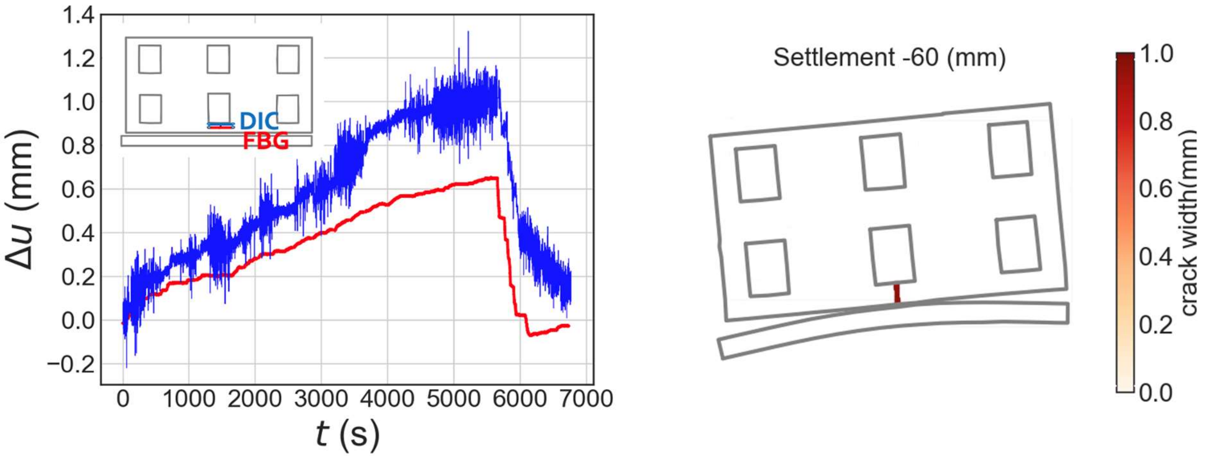

Figure 4 – (left) Crack opening measurements from fibre optic sensors ('FBG') and cameras ('Virtual LVDT') for the reference specimen, **(right)** alongside a visual description of the location and width of the crack

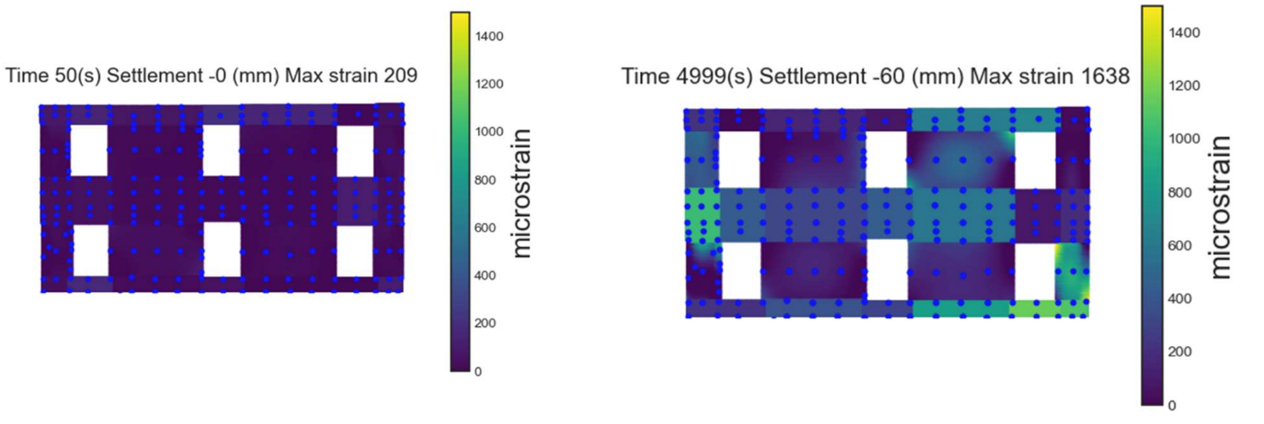

Figure 5 – Visual description of strains estimated from displacements at the **(left)** beginning and **(right)** end of the test for the reference specimen.

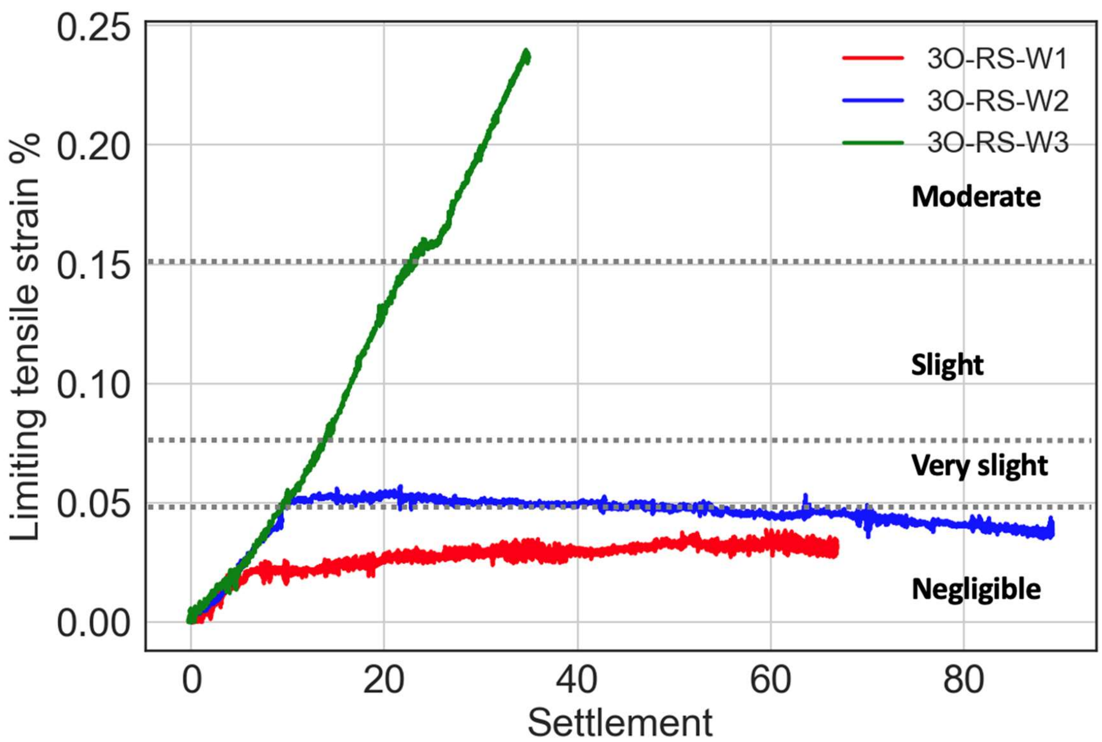

Figure 6 – Plot showing the variation of tensile strain with increasing settlements for the reference specimen. Results for both regular loading (W1), doble regular loading (W2) and additional loading at ground floor window sills (W3) are reported. Key indicators are significantly larger for W3, where significant damage was observed.

3. Conclusions

This experimental campaign resulted in the collection of valuable data that improves our understanding of the response of masonry assets to ground movements. It highlights structural aspects which significantly influence the response. Furthermore it provides the much-needed data to evaluate the damage categorisation criteria and the associated assessment procedures.

The data that was gathered during this project will support the development of improved ways to monitor building response to detect damage. It will also enable the development of more efficient numerical modelling techniques. In this way, the project will contribute to safeguarding historic masonry assets while enabling safe underground construction in their vicinity. The techniques that are being developed as a part of this project are widely applicable and can be adapted to address other structural forms (e.g. framed buildings, bridges) and materials (e.g. concrete and steel).