

## STRUCTURAL PROPERTIES OF UNREINFORCED MASONRY WALLS CONSIDERING CONSTRUCTION QUALITIES

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**Keywords:** unreinforced masonry walls, diagonal tension tests, construction quality, non-structural component, bed-joints, head-joints

**Abstract.** *Non-structural unreinforced masonry (URM) walls are generally consisted of cement bricks and mortar used for joint material. Bricks in masonry works should be completely glued on bed and head-joints with sufficient thickness. In typical masonry construction, variation of thickness and recess of bed and head-joints is inevitable and they are important physical parameters that can be used in determining the construction quality of masonry works. Thus, it is necessarily required to investigate the influence of construction quality on the structural properties of an URM wall. As preliminary investigations, this study experimentally evaluates the effects of construction quality to the diagonal tension behavior of a masonry unit. The effects are discussed with selected test parameters, thicknesses and recesses of joints which can be considered to be critical quantities to erection time related to the construction quality of the test specimens. Test results present that the failure modes of the specimens are considerably dependent upon the construction qualities and their strength and elastic modulus increase in the specimen with better construction quality presenting the smaller recess and the larger thickness of the bed and head-joints.*

## 1 INTRODUCTION

Unreinforced masonry (URM) walls used as a non-structural element in building construction have been commonly implemented for architectural space zoning. The lessons learned from historical earthquakes have demonstrated that non-structural URM walls can be vulnerable to even low intensity of seismic attacks resulting in free structural damage to a building structure. Under cyclic loading, they suffer fatal failures classified into toe compression failure, rocking, bed-joint sliding, diagonal cracking and overturning failures. Thus, current seismic design codes, such as AIK [1] and ASCE [2], prescribe the design requirements for non-structural URM walls in order that their seismic performance improves and, in turn, the seismic damage is limited under even severe ground motion shaking.

A nonstructural URM wall consists of concrete bricks laminated by mortar without any reinforcements for structural integrity. Thin layer glue-mortar is applied to the perimeter sides of a brick to make bed and head-joints in the horizontal and vertical directions of a wall, respectively. Bricks in a masonry unit are manufactured with relatively excellent quality control. However, although construction specifications [3] for masonry works recommend that bed and head-joints of sufficient thickness (usually larger than 10 mm) be installed, the quality of in-situ mortar bed and head-joint works is still hardly controlled in a construction site. The construction quality of mortar joint works can be quantitatively represented by their thickness and recess which will be chosen as test parameters for this study.

In order to assess the structural behavior of an URM wall resulting from such complicate material composition, the structural properties of a masonry unit first need to be precisely evaluated. This is carried out by compressive tests of prisms and diagonal tension tests of masonry units. This study investigates the influence of the thickness and recess of mortar joints on the structural properties which can be obtained from diagonal tension tests of a masonry unit. To do this, specimens for diagonal tension tests of masonry units were prepared with three construction qualities, “*Good*”, “*Fair*” and “*Poor*” which can be classified by masonry piling time correlated with apparent physical test parameters, the thickness and recess of mortar joints. The testing parameters are statistically analyzed according to the construction qualities. Also, test results of the masonry unit specimens manufactured with different construction quality are discussed in terms of their strength and elastic modulus. This *pilot* test program intends to demonstrate the relation between the structural properties and the construction quality of masonry walls which can become basis information on the seismic evaluation of existing and new masonry building structures.

## 2 DESCRIPTION OF TEST SPECIMENS

The structural behavior of a non-structural URM wall mainly depends on the properties of masonry units affected by the construction quality which is influenced by a lot of factors including the workmanship of skilled laborers, working environments, working temperatures, working space, etc. All of factors related to construction quality of masonry works are closely represented by a masonry piling time. It was known throughout interview with skilled laborers that they are capable of piling only about 120 bricks in carrying out masonry works according to very strict working manual while they can pile more than 200 bricks under the allowance of poor construction quality. This study considers a masonry piling time as the main factor which can determine the construction qualities of masonry works.

Figure 1 shows the shapes and dimensions of specimens for diagonal tension test specimens according to ASTM [4]. The masonry unit specimens with 390 mm width, 392 mm height and 90 mm thickness were made with a total 12 cement bricks which were piled to 6 layers. The dimensions of each brick are 190 mm × 90 mm × 57 mm. According to general

construction specifications for masonry works, the thickness  $t_{bj}$  of both bed and head-joints is planned to be larger than 10 mm and straight head-joints are avoided. Note that during construction of the specimens, a value of  $t_{bj}$  for each specimen would be changed and would also have spatial variation within an individual specimen. A total of 30 specimens was prepared and 10 specimens were constructed with each construction quality classified into “Good”, “Fair” and “Poor” which are dependent upon the masonry piling time  $T$ . Table 1 summarizing the statistics of  $T$ s shows that mean values of  $T$ s increase for the specimens with better construction quality. Regardless of the construction qualities, the coefficients of variation COVs are similar. This means that all specimens categorized into the same construction quality maintain the similar degree of variation of masonry piling times.

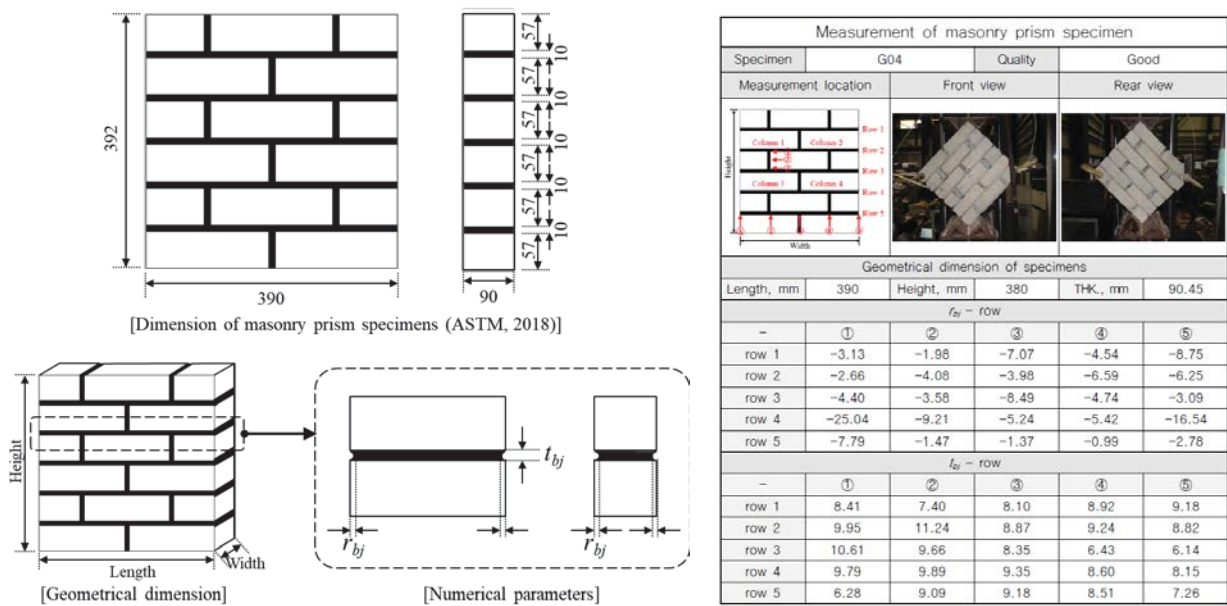


Figure 1: Dimension of specimens and numerical parameters representing masonry construction qualities

	Good	Fair	Poor
Mean, $T$ , sec	231	113	105
Standard deviation, sec	19.4	12.4	9.2
Coefficient of variation, COV, %	8.4	8.6	8.7

Table 1: Statistical information for construction time of masonry unit specimens

Values of  $T$ s are considered as the main index of construction quality in manufacturing the specimens. More physical parameters are required to verify the relation between construction quality (represented by masonry piling time  $T$ ) and the structural properties of the masonry unit specimens. This study considers the thickness  $t_{bj}$  of both bed and head-joints and their recess  $r_{bj}$  from the brick surface as the apparent testing parameters, shown in Figure 1. Values of  $t_{bj}$  and  $r_{bj}$  of all the specimen were examined after curing. For each specimen, a total of 37 measurements (12 at head joints and 25 at bed joints) was measured using a digital Vernier caliper.

The distributions of  $t_{bj}$  and  $r_{bj}$  values measured at the bed and head-joints in the specimens are found in Figures 2 and 3. Regardless of types of joints, the larger  $t_{bj}$  values and the smaller absolute values of  $r_{bj}$  are founded at the masonry unit specimens erected with better construc-

tion quality. A mean of  $t_{bj}$  values is the smallest at the head-joints for the *Poor* specimens while the corresponding mean values for the *Good* and *Fair* specimens are relatively close to 10 mm which is the planned joint thickness. Values of  $t_{bj}$  larger than 10 mm are found in the head-joint for some *Good* specimens. Mortar filling in bed-joints is better than in head-joints, which magnifies the variation of  $r_{bj}$  values measured in head-joints.

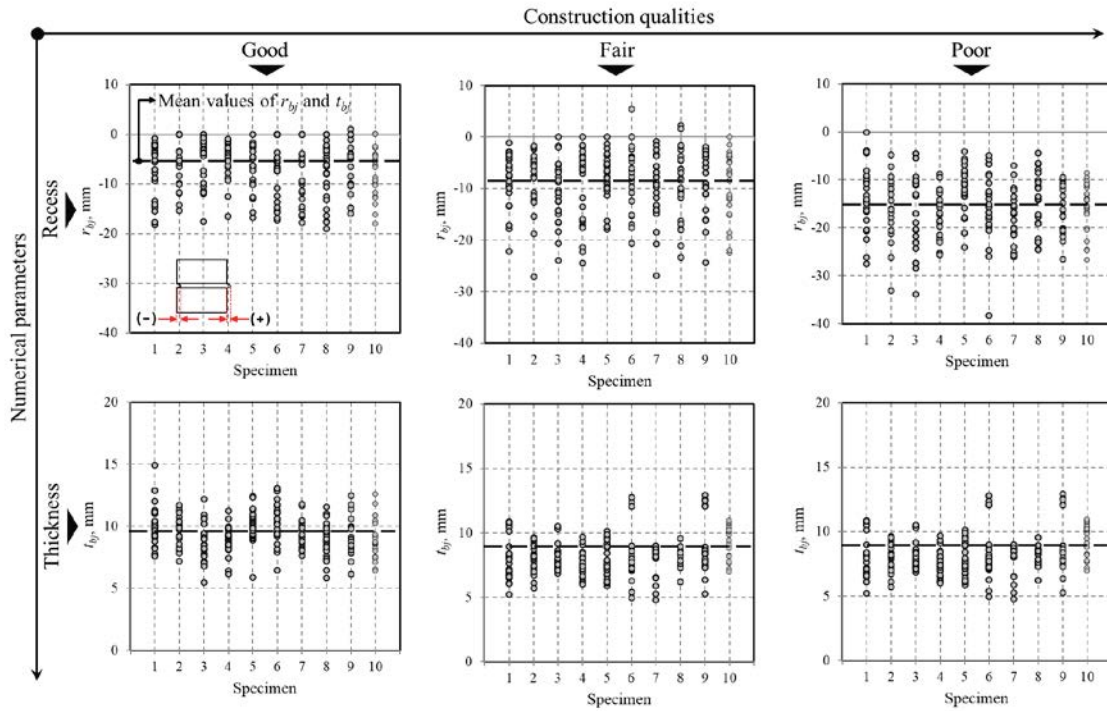


Figure 2: Distribution of numerical parameters measured at bed-joints in specimens

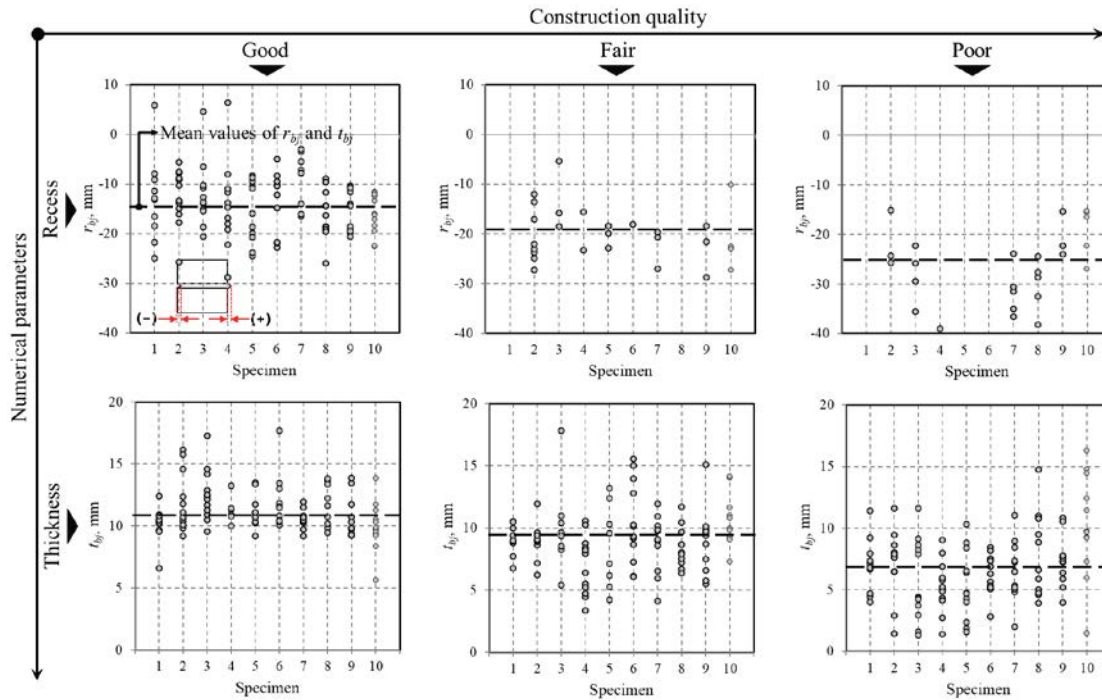


Figure 3: Distribution of numerical parameters measured at head-joints in specimens

Statistical spatial variations of  $t_{bj}$  and  $r_{bj}$  values measured at both of the bed and head-joints in the specimens were investigated and summarized in Figure 4. Expected values of  $r_{bj}$  measured at the bed-joints are the smallest at their center and are increased at the edges while those of  $t_{bj}$  are relatively constant along a joint line. Unlike the bed-joints, means of  $r_{bj}$  values measured at the head-joints of the *Good* specimens are the largest at their center. For the *Fair* and *Poor* specimens, means of  $r_{bj}$  values at the head-joints are smaller as the distance from the bottom bed-joint is increased. Again, the largest spatial variation of both  $t_{bj}$  and  $r_{bj}$  values is also observed at the *Poor* specimens even if there is still some degree of spatial distribution in the *Good* specimens.

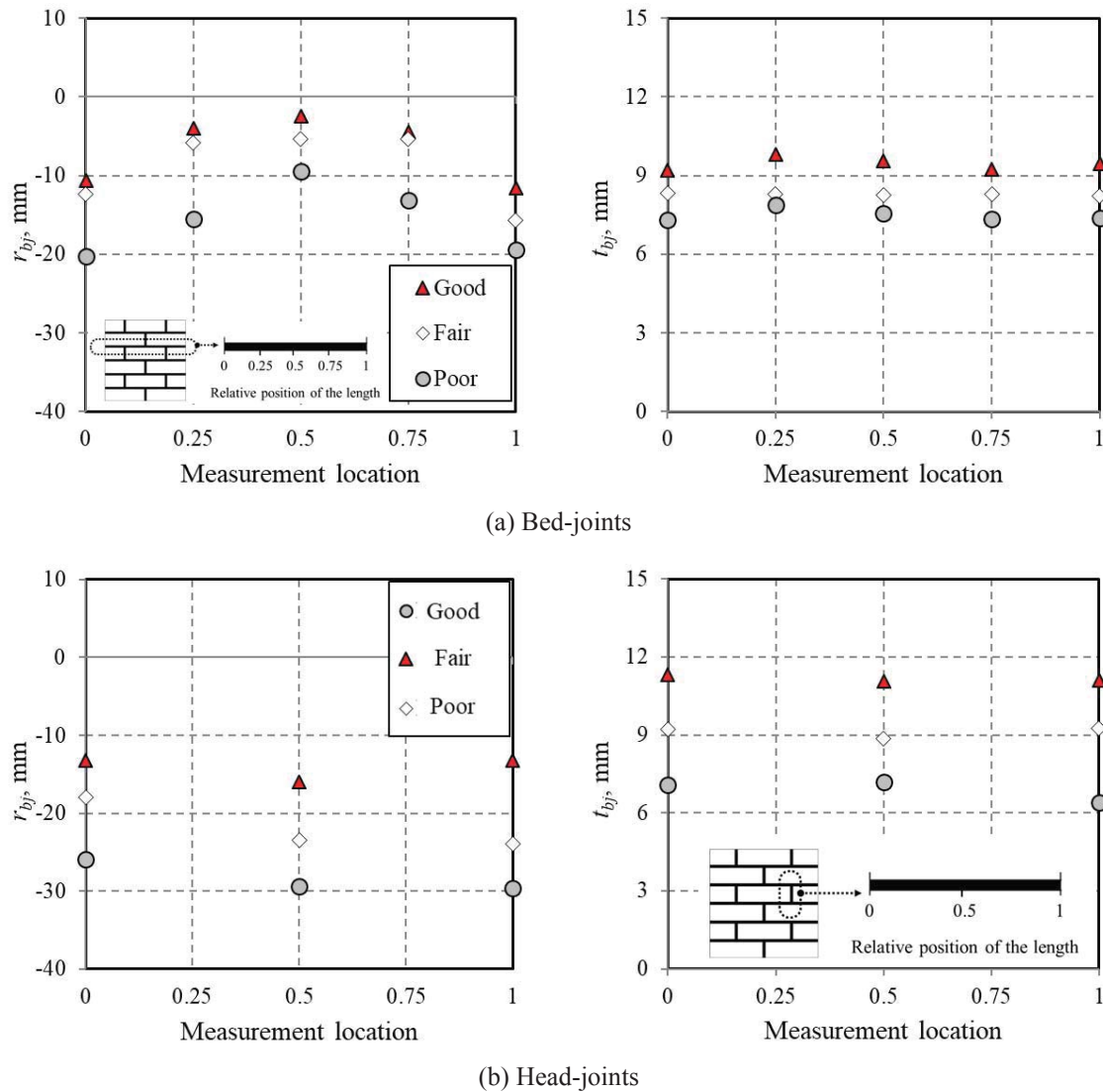


Figure 4: Mean numerical parameters at measurement locations

### 3 EFFECTS OF CONSTRUCTION QUALITY ON DIAGONAL TENSION BEHAVIOR OF TEST SPECIMENS

Diagonal tension tests were carried out with the Universal Testing Machine with 500 kN capacity. Figure 5 presents crack patterns observed at the end of each test. Also, the failure



modes relied on the construction quality of the specimens are shown in the figure. In the *Good* specimens, cracks parallel to the loading direction developed along bed and head-joints alternately. A few cracks were also found in bricks. Similar crack pattern was observed in the *Fair* specimens. However, for the *Poor* specimens most of cracks were developed along one of bed-joints where is relatively short of filling mortar. Compared to the *Good* and *Fair* specimens, the total travelling length of cracks in the *Poor* specimens was shortened, which causes a brittle mode.

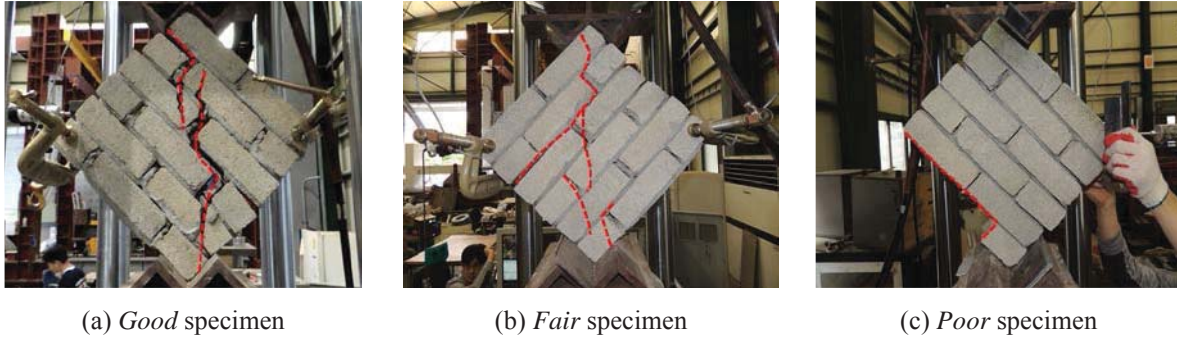


Figure 5: Dominant failure modes of masonry unit specimens according to construction quality

Diagonal tension tests are typically performed to find out the direct shear stress and modulus which are important structural properties used for the seismic evaluation of a non-structural URM wall. Figure 6 contains measured shear stresses,  $\tau_m$  at the maximum applied loads and shear modulus,  $G_m$  of the specimens. In this figure, solid parallelograms represent their mean values of the *Good*, *Fair*, and *Poor* specimens. The mean values of  $\tau_m$  are, respectively, 0.56, 0.44 and 0.35 MPa for the *Good*, *Fair*, and *Poor* specimens, which demonstrates their dependence on the construction quality. The normalized means of  $\tau_m$  values to that of the *Good* specimens,  $\tau_{m(good)}$  are 0.79 and 0.63 for the *Fair* and *Poor* specimens, respectively. Note that even the mean of  $\tau_m$  measured at the *Poor* specimens is still larger than the codified shear strength of 0.2 MPa [5] which is close to the smallest shear stress in the *Poor* specimen. The correlation of shear modulus with construction quality of masonry unit are similar to that of shear stress. The normalized means of  $G_m$  values to that of the *Good* specimens,  $G_{m(good)}$  are 0.80 and 0.57 for the *Fair* and *Poor* specimens, respectively.

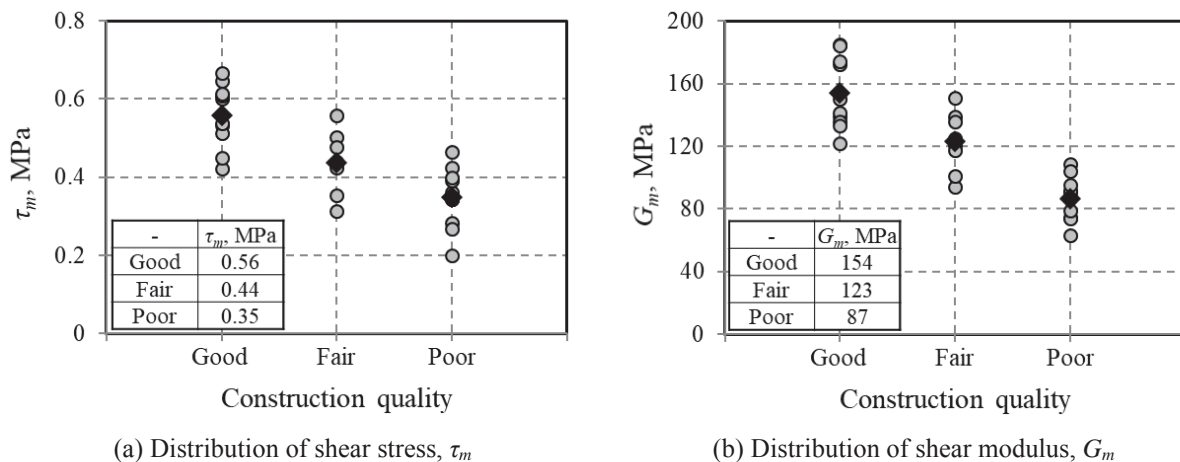


Figure 6: Distributions of mechanical properties of masonry unit specimens

The normalized  $\tau_m$  and  $G_m$  values are further analyzed to investigate effects of combination of the parameters,  $t_{bj}$  and  $r_{bj}$ , in detail. To do this, a normalized net mortar filling area factor,  $\Lambda$  defined as a ratio a net mortar filling area,  $(A_{bj} - t_{bj} \times r_{bj})$  to the total joint area  $A_{bj}$  is introduced. Figure 7 shows the relations between the normalized  $\tau_m$  and  $G_m$ , and  $\Lambda$  values for each type of joints in the all specimens. Linear correlation is clearly presented in the bed-joints rather than the head-joints. This is due to a factor that  $\Lambda$  values of the head-joints are not correlated with the construction quality, as shown in the figure where some of the *Poor* specimens have the head-joints with mortar-filling area that is larger than the corresponding of the *Good* and *Fair* specimens. In the bed-joints,  $\Lambda$  values increase for the specimens constructed with better quality. Most of the normalized  $\tau_m$  and  $G_m$  values can be conservatively estimated using a linear equation established by considering one standard deviation from a trend line shown as a solid line in the figure.

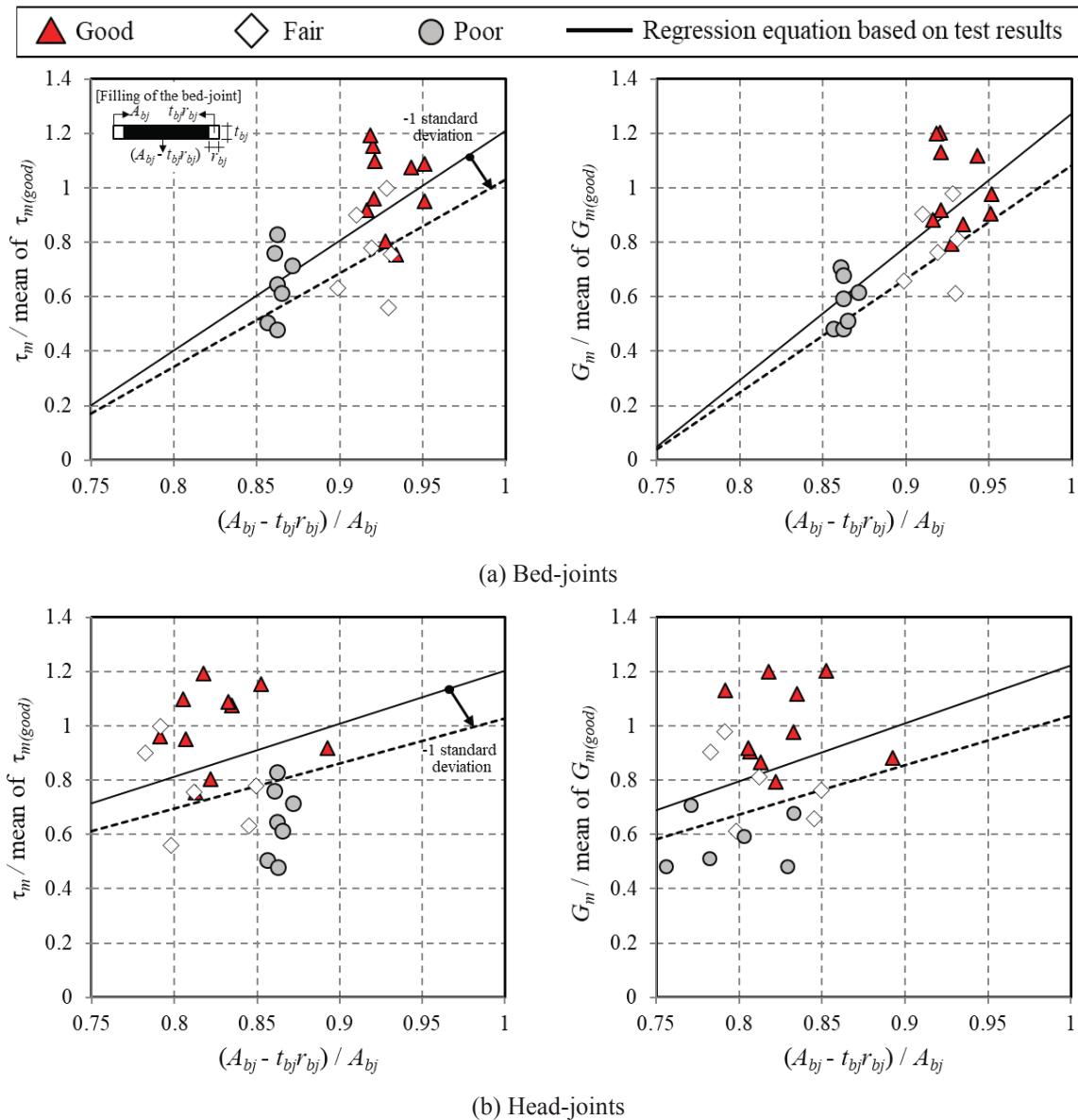


Figure 7: Relation between numerical parameters and filling of the bed and head joints measured at unit specimen

## 4 CONCLUSIONS

This study is carried out diagonal tension tests of masonry units manufactured with construction qualities of “*Good*”, “*Fair*” and “*Poor*” that can be differentiated by the thickness and recess of mortar joints. The effects of construction quality on the structural properties of the specimens are investigated. This *pilot* test program intends to provide basic information on the influence of construction qualities on the seismic capacities of nonstructural URM walls.

A total of 30 specimens with 390 mm width, 392 mm height and 90 mm thickness was prepared. Of them, 10 specimens were constructed with each construction quality classified into “*Good*”, “*Fair*” and “*Poor*”. This study considers the thickness  $t_{bj}$  and the depth of recess  $r_{bj}$  as parameters representing construction qualities. The largest  $t_{bj}$  values and the smallest absolute values of  $r_{bj}$  were founded in the *Good* specimens while a mean of  $t_{bj}$  values was the smallest at the head-joints for the *Poor* specimens. In statistical spatial variations of  $t_{bj}$  and  $r_{bj}$  values, the largest spatial variation of both  $t_{bj}$  and  $r_{bj}$  values was also observed at the *Poor* specimens.

The *Good* and *Fair* specimen’s cracks developed into bed and head-joints alternately. In the *Poor* specimens, most of cracks were developed and propagated on a single bed-joint, which causes a brittle failure mode. The mean shear stresses are, respectively, 0.56, 0.44 and 0.35 MPa for the *Good*, *Fair*, and *Poor* specimens. Similar to the mean shear stresses, the correlation of shear modulus with construction quality is presented. There exists the linear correlation between normalized shear stress and modulus and a normalized net mortar filling area factor in the bed-joints. The normalized shear stress and modulus are increased with the increase in mortar filling area of the specimens.

## ACKNOWLEDGEMENT

This research was supported by a grant (20AUDP-C146352-03) from the Architecture & Urban Development Research Program funded by the Ministry of Land, Infrastructure and Transport of the Korean Government.

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