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Static and Dynamic Properties of Clay Brick Materials

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Abstract

It is commonly known that materials behave differently under static and dynamic loadings. Clay brick is a vastly used building material. Systematic studies on the dynamic material behaviors of clay bricks are still very limited in the open literature, and the dynamic effect on clay brick material properties is not well investigated. This study investigates and quantifies the dynamic mechanical properties of clay bricks. Firstly, low-speed and high-speed compressive tests are carried out on three types of clay bricks, i.e. Copper Brown, Limestone Hue and Common Solid, made with Western Australia clays. The compressive strengths, corresponding failure strains and Young's modulus of the three different types of brick materials at different strain rates (from 1.67×10^{-6}/s to 0.08/s and 190/s to 337/s) are quantified. The test results show the compressive strength is very sensitive to the strain rate effect, while the failure strain and Young's modulus also exhibit strong strain rate dependency in the high strain rate range but appears to be less sensitive to strain rate in the low strain rate range. Based on the test results, empirical relations of dynamic increase factor (DIFs) for compressive strength, failure strain and Young's modulus with respect to strain rate are derived for each type of brick materials. Discussions and comparisons are made on the dynamic fracture processes and specimen fragments to explain the dynamic enhancement in brick mechanical properties. Secondly, the dynamic tensile properties of clay bricks are investigated. Quasi-static and dynamic tests are carried out on these three types of clay brick materials. Both direct tensile test and indirect split-tensile test (Brazilian disc test) are conducted to determine the brick tensile properties at various strain rates. Dynamic tensile strength, corresponding failure strain, Young's modulus at strain rates between 1.33×10^{-6}/s and 26/s are determined. Correlation between dynamic split-tensile strength and dynamic direct tensile strength is examined, and a conversion relationship is proposed. The results are compared with existing data on brick, mortar and concrete materials. The empirical formula of DIF (dynamic increase factor) for brick tensile strengths at different strain rates are derived for easy and accurate engineering analysis and numerical modelling of clay brick response under dynamic loading.

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Publications Arising from This Thesis

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3. Zhang, X., **Chiu, Y-W.**, Hao, H., Hsieh, A., Salter, N., Cui, J., 2018, Dynamic Compressive Material Properties of Clay Bricks at Different Strain Rates, Construction and Building Material, 192, pp. 754-767.
4. Zhang X, **Chiu Y-W**, Hao H, Hsieh A, Dight P, Liu K. 2020, Dynamic Compressive Properties of Kalgoorlie Basalt Rock. International Journal of Rock Mechanics and Mining Sciences. 2020; 135:104512.

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Chapter 1 Introduction

1.1 Background

Brick material is widely used for masonry construction in Australia and throughout the world. They exist in many places such as historical buildings, churches, schools or residential houses. Brick structures are relatively low cost and have good thermal and sound insulation performance comparing with reinforced concrete and steel structures. They are also, in general, more robust in comparison to timber and other structures. Therefore, masonry buildings are overwhelmingly constructed as low- and mid-rise residual structures.

During the design life, a structure could be subjected to extreme loadings such as earthquake load, impact load from a vehicle or rock fall, and blast load from terrorist bombing or accidental explosions. Since material behaves differently under dynamic and static loading, accurately predict the response and performance of masonry structures under dynamic loading require good understandings of dynamic material properties at different strain rates [1-4]. While there are extensive studies on concrete and rock materials, research on the dynamic properties of clay brick is still limited. This is primarily because clay brick structures normally have low blast and impact resistance capacity. Nevertheless, since brick structures are overwhelmingly constructed all over the world, which could be subjected to impact loading from cyclone debris, vehicle impact, and accidental explosion and hostile blast, it is therefore important to properly understand the dynamic material properties of bricks for more accurate analysis and design of brick structures for people and structure protection, especially many iconic and culture heritage structures consist of masonry components, i.e., walls and pillars.

In the past few decades, the dynamic behaviours of construction materials such as concrete, steel, glass, rocks, and rubber have been extensively studied [2, 5-9]. For instance, the concrete compressive strength of concrete can increase up to 2 times under uniaxial compression and five times under direct tension at a strain rate of 100/s [10]. The design code UFC-3-340-02 [11] by the Department of Defence, USA, recommends a dynamic increase factor of 1.4 at a strain rate of 40/s, indicating a 40% increase to concrete strength. In evaluating the strain rate effect, dynamic increase factor (DIF), which is the ratio of dynamic material strength/modulus over static strength/modulus, has been widely employed to model the dynamic enhancement effect. Since the DIF of certain material varies with respect to the strain rate it experiences, a formula of DIF versus strain rate is commonly utilized to represent the change of dynamic material properties with respect to the static material properties.

1.2 Scope of this study

The aim of this study is to experimentally investigate the quasi-static and dynamic material properties of clay brick materials used in Western Australia. Three different types of clay bricks corresponding to low-strength, mid-strength and high-strength popularly used in construction in Western Australia are studied. Both the compressive properties (Section 4) and the tensile properties (Section 5) are studied. For the compressive properties, unconfined uniaxial tests under quasi-static and dynamic states are conducted covering strain rates from 1.67×10^{-6}/s to 337/s. Similarly, for the tensile properties, quasi-static and dynamic tests are carried out covering strain rates from 1×10^{-6}/s to 25/s. The different tensile testing methodologies, including split-tensile test and direct tensile test, are carried out to determine the tensile properties. The testing results are evaluated and correlated together. The brick material properties at different strain rates are revealed, and empirical formulae are derived based on the testing data for engineering application.

1.3 Thesis organization

This thesis consists of Six chapters as follow:

1) Chapter 1 presents a brief background introduction. The objectives and scope of this research are described in this chapter.
2) Chapter 2 presents the literature review. Material dynamic testing methods are reviewed, which focuses on the determination of material tensile properties and correlations of material tensile strengths obtained from different testing methods. The dynamic material properties of brick and other commonly used construction materials are also reviewed. The influence

factors to the material dynamic properties are summarized.

3) In Chapter 3, the methodology employed in this study is presented. The preparation of clay brick specimens for this study is detailed. Then, the testing methodology for quasi-static and low-speed tests are presented, which are followed by the dynamic compressive test. The dynamic tensile tests, including both split-tensile test and direct tensile test, are presented. A new clamping method for the dynamic direct tensile test is introduced, and the testing results is compared with other conventional clamping methods.
4) Chapter 4 presents the quasi-static and dynamic compressive properties of clay bricks. Three types of clay bricks are tested under quasi-static state, low-speed and high-speed dynamic states. Brick compressive strength, Young's modulus and ultimate strain at different strain rates are determined. The empirical formula of DIF versus strain rate for each brick is derived.
5) Chapter 5 presents the tensile properties of clay bricks. Both direct tensile test and split-tensile test are carried out at quasi-static and dynamic states. Correlation between the direct tensile strength and split-tensile strength is made. The tensile strength, corresponding failure strain and Young's modulus at different strain rates are quantified. With available testing results, the empirical formula of DIF for brick tensile strengths at different strain rates is derived.
6) Chapter 6 concludes this research work and gives some recommendations on future works in this area.

Chapter 2 Literature Review

This chapter presents the literature review for this study. Material dynamic testing methods are firstly reviewed. Then, the focus is placed on the determination of material tensile properties and correlations of material tensile strengths obtained from different testing methods. The dynamic material properties of commonly used materials, such as concrete, mortar, and rock, are also reviewed. The influence factors to the material dynamic properties, including inertia effect, friction effect, specimen moisture content and etc., are reviewed and summarized.

2.1 Dynamic testing technology

Different loading techniques and experimental equipment have been introduced and developed to determine material mechanical properties at different strain rates. Reference [12-14] provide comprehensive reviews of available testing methods and systems. Commonly utilized testing systems include screw-driven loading frames, servo-hydraulic machines, drop weight impact systems, high-speed servo-hydraulic machines, Split-Hopkinson Pressure Bar (SHPB) systems and plate-impact systems. The screw-driven load frame and servo-hydraulic machine can test material strength at a strain rate between 10^{-5}/s to 1/s. Drop weight impact system and high-speed hydraulic machine can normally cover the strain rates ranging between 1/s and 200/s depending on the specimen length. SHPB system and plate-impact system are commonly used to determine material strength at high strain rates ($\dot{\varepsilon} \geq 100$/s). One of the fundamental differences between quasi-static/low-speed test and high-speed dynamic tests is that wave propagation and inertia effects become pronounced at high strain rates. To achieve a valid test result, it is therefore important to ensure the stress and strain inside the specimen are uniforms (dynamic equilibrium state). For low-speed tests, there is enough time for the elastic stress wave to travel within the specimen to achieve stress equilibrium. In a dynamic test, dynamic stress uniformity is achieved only after the impact induced waves have propagated back and forth through the specimen for a minimum number of times. It is normally requires at least three reverberations [5, 15] or five-ten reverberations [16] of the stress wave in the specimen before it fractures for a SHPB test.

2.2 Static and dynamic tensile testing methods

In order to determine the tensile properties of brittle materials, there are a few methods commonly employed, i.e., direct tensile test, in-direct split-tensile test (Brazilian disc test), flexural bending test, dynamic spalling test, etc. A direct tensile test is ideal, in which the specimen is under a uniform uniaxial stress state. However, it is challenging to perform such tests because the specimen needs to be properly attached at the two ends along the loading direction, where the end effect could lead to premature failure around the fixing point of a sample. This is because the adhesive and the tested material have different lateral strains due to the different modulus and Poisson's ratio, resulting in extra shear stress developed near the contacting surface [17]. A dumbbell shape specimen is commonly used to minimize the end effect, which nevertheless is not straightforward to prepare, particularly for brittle materials like brick and rock, which cannot be cast into the complex shape. Moreover, stress concentration often occurs at the "neck" of the dumbbell specimen resulting in inaccurate test results. Therefore, the direct tensile test is very "expensive" in terms of specimen preparation and testing efforts [18]. Alternatively, indirect split-tensile tests are popularly conducted for brittle materials. In a split-tensile test, a diametric compression is applied to a circular disk specimen. Because of the specimen's lateral expansion, uniform tensile stress is generated across the loaded diameter accompanied by vertical compressive stress. A validated split-tensile test requires the tested material being isotropic, homogeneous and linearly elastic before brittle failure occurs [19]. Also, to ensure a split-tensile test is valid, cracks need to initiate from the centre of a specimen [3]. Since the specimen is under a different stress state (compression induced lateral splitting), the split-tensile strengths are mostly found to be different from direct tensile strength [20, 21]. The three-point bending test is another commonly used method to determine the flexural tensile strength of concrete and other materials, but it is not suitable for brick and rock, which are difficult to prepare into a beam. Similarly, the spalling test has also been employed to measure the dynamic tensile strength of brittle materials. A compressive stress wave is generated and transmitted into a long and slender specimen in a spalling test, which propagates to the free end of the specimen and reflects. Since the tensile strength of brittle materials is normally much smaller than their compressive strengths, the reflected tensile stress wave will lead to the tensile failure of the specimen so that the tensile strength of the specimen can be determined. Because a spalling test requires a long specimen for stress wave to propagate and reflect, it is apparently not suitable for brick either. Therefore, the suitable testing methods for determining material tensile properties of clay bricks are direct tensile test and split-tensile test.

2.3 Correlation of tensile strengths from different testing methods

For the same materials, the measured direct tensile strength and split-tensile strength are mostly different. Many researchers [22-24] found the split tensile strength of a material is usually higher than its direct tensile strength, while a few researchers reported a lower split-tensile strength [25, 26]. There are a few possible reasons leading to the different tensile strengths measured for concrete material. Firstly, split-tensile strength is calculated based on the homogeneous material assumption, while concrete is a non-homogeneous material, which could result in an inaccurate higher split-tensile strength measured in tests. Secondly, in comparison to the direct tensile test where the failure of a specimen occurs at the weakest cross-section, in a split-tensile test, failure is deemed to occur along the centre of the specimen, which could involve stronger components in concrete such as higher strength aggregates. Therefore, a higher split-tensile strength could be measured. However, these may not necessarily be valid under dynamic loading condition. Because of the fast propagation of stress wave, there is not sufficient time for failure to develop at the weakest section under direct tensile test. Instead, many studies found in the dynamic direct tensile test, a more flatten fracture surface is often observed with the failure of strong aggregates on concrete specimens [7, 27]. Thirdly, considering the difficulty in conducting a direct tensile test, eccentricity may occur, which may lead to a smaller test result of the uniaxial tensile strength [22]. Last but not least, in a direct tensile test where the tensile stress and strain is uniform in the specimen along the loading direction. In a split-tensile test, tensile stress is generated in the lateral direction perpendicular to the compressive stress due to Poisson's ratio. Under this combined stress state, a higher principal strain is developed than that in the uniaxial state. Consequently, the split-tensile strength should be lower than that of the direct tensile strength. The above discussions are based on testing data and observations on different materials under static loading condition. Their suitability under dynamic loading condition is not known yet.

Considering the different strengths of material are obtained from split-tensile, and direct tensile tests, conversion between these two strengths have been proposed. For rock, Perras and Diederichs [28] summarized a wide range of data on various rocks. They found the ratio between the direct tensile strength and split-tensile strength is 0.9 for metamorphic rock, 0.8 for igneous rock and 0.7 for sedimentary rock. For mortar, Ramedh and Chopra [29] suggested a ratio of 0.41 to 0.75, and Ali et al. [30] found a ratio of 0.69 to 0.96 for mortars with different water/cement ratios. Many studies have also been conducted for concrete to establish a relation between the direct tensile strength and split-tensile strength, which varies significantly. Popovics [31] conducted a comparative study to correlate the concrete compressive, direct tensile, split-tensile strengths. The conversion factor obtained from different researchers varies from 0.41 to 0.93. Pincus and Gesund [32] reported a ratio of 0.9 for converting the split-tensile strength into direct tensile strength of concrete. Bonzel [33] suggested a ratio of 0.75 and observed this ratio decreases when concrete tensile strength increases. All these studies were for quasi-static loading conditions. There is no study available in the literature to define the conversion factors of dynamic tensile strength of materials obtained from split-tensile and direct tensile tests at different strain rates.

2.4 Static material properties of brick material

The quasi-static compressive strength of brick material could vary significantly between 5MPa and 50MPa. This is due to differences in material compositions and manufacturing process. Australian Standard AS/NZS 4455 Part 1 [35] requires the uniaxial unconfined compressive strength not less than 3 MPa. It is commonly known concrete tensile strength is about one tenth of its quasi-static compressive strength. Many studies have been conducted to identify the relationship between static compressive strength and tensile strength of concrete. For instance, the concrete flexural tensile strength was found 8 to 11% of the compressive strength for high strength concrete and 9 to 12.8% for low strength concrete (below 25 MPa) [34]. Surprisingly, there are very limited studies in the literature to quantify the tensile strength of brick materials, let alone the relationship between the compressive and tensile strength. This is because brick structures when subjected to tensile force normally fail at joint between mortar and brick. Nevertheless, when subjected to dynamic loading such as earthquake, impact, and blast loading, brick tensile damage is commonly observed. Therefore, it is necessary to properly study both the compressive and tensile strength of brick materials.

2.5 Dynamic material properties of bricks: current understanding

Many efforts have been paid to investigate the dynamic material properties of various construction materials, including concrete, steel, rock, glass, and polymers etc. [2, 5, 7-9, 39, 40]. But there is limited research on dynamic properties of brick materials [41-43], and among the few existing experimental studies, discrepancies could be found from the testing results. DIF of bricks is generally from 1.2 to 3.0 for compressive strength and up to 3.0 for tensile strength. Larcher et al. [41] conducted the SHPB test on bricks and found a DIF of 1.38 at a strain rate of 189 /s. Pereira et al. [43] tested a good amount of brick specimens with a drop-weight impact testing system. Brick strength at strain rates between quasi-static state to 176/s was quantified. The study found the compressive strength can vary from 15.30 MPa (quasi-static) to 37.64 MPa (at strain rate 57 /s) for the studied brick. The most comprehensive and widely referenced dynamic test on clay brick was by Hao and Tarasov [42]. They utilized a specially designed triaxial static-dynamic testing machine to maintain a constant loading speed at high cross-head velocities. The unconfined compressive strength of clay bricks at strain rates between 2.1×10^{-6}/s to 160/s was determined. It is worth noting that the specimens tested in reference [42] adopted specimen length/diameter ratio of 2:1, which means a high axial inertia effect could likely have resulted especially in the high strain rate regime. In addition, only a single type of clay brick was tested. Many different types of bricks which have different material properties are used in construction. Studying the dynamic properties of clay bricks with different chemical compositions will not only augment the literature and database of the strain rate effect on brick materials and lead to more accurately analyse and design of masonry structures subjected to high-rate dynamic loads. Due to limited test results available on clay brick dynamic properties, most current researches on masonry structures subjected to impact and blast loadings have to employ static material properties for bricks or dynamic material properties at certain strain rates only [41], which not necessarily led to accurate predictions of structural responses. Therefore, a comprehensive and systematic study on the dynamic material properties of brick materials will contribute to a more accurate and economical design of masonry structures.

2.6 Influence factors to dynamic material properties

Despite the fact that it is commonly accepted that material behaves differently under dynamic loading comparing to that under static loading condition. There has been a dispute and debate on the observed dynamic increment to material properties in dynamic impact tests for years about whether it is a material property or this is mainly a structural effect associated with the dynamic tests until recently; some general consensus has been reached. The dynamic increase effect observed on material properties can be attributed to material properties and structural effect (inertia effect and end friction effect). The structural effect, i.e. axial and lateral inertia confinement effects and end friction effect, partially contribute to the material strength and modulus enhancement at high strain rates. In the following sections, these influence factors to the dynamic material properties are reviewed and summarized:

2.6.1 Influence of inertia effect

Under dynamic loading condition, stress wave in the specimen leads to inertia effect in both axial and lateral directions due to Poisson's ratio. The magnitude of inertia effect to the stress depends on the density, Poisson's ratio, specimen length and diameter [44]. To minimize the axial inertia effect, an optimized length-over-diameter ratio of $\sqrt{3\nu}/2$, in which ν is Poisson's ratio, has been derived through close-form solution [45]. Under high-speed compression, the specimen inevitably deforms laterally due to Poisson's ratio. The lateral deformation leads to inertia force as a confinement effect. The influence of lateral inertia confinement on dynamic compressive strength of rock, concrete etc., has been widely studied [7]. For example, Li and his co-workers [46] carried out a numerical study on tubular specimens and found lateral inertia effect contributes significantly to the dynamic enhancement of material compressive strength when the strain rate is greater than a threshold. Hao et al. [47] carried out a numerical simulation to study the lateral inertia effect of three types of rock materials and proposed empirical formulas for 25mm diameter granite, limestone and tuff to quantify the contribution of lateral inertia confinement to the dynamic increase in rock strength obtained from impact tests. A numerical study by Zhou and Hao [10] quantified the contribution of the inertia confinement effect under a high strain rate (Figure 2-1), where an additional 20% strengthening effect is found under strain rate 1000 /s.

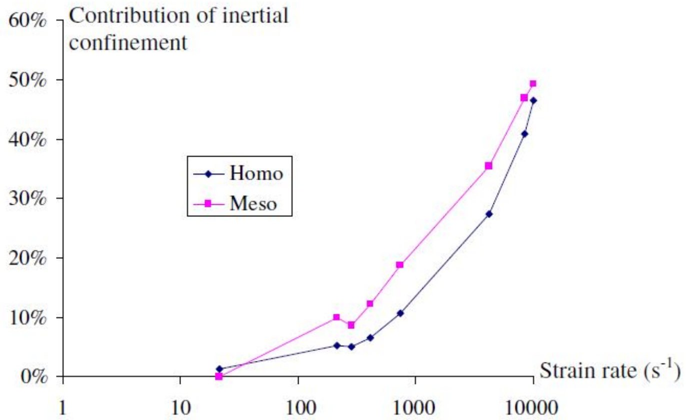
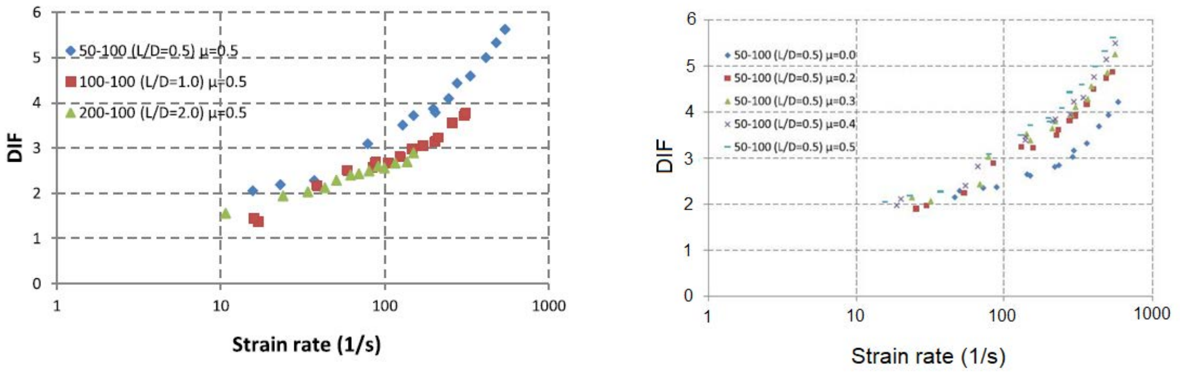


Figure 2-1 Inertia confinement effect at various strain rates [10]

2.6.2 *Influence of end friction*

In dynamic tests, another important structural effect that shall be paid attention to is the end friction confinement. The friction existing at the interfaces between the specimen and the loading plates provides constraints to the lateral deformation of the specimen under high-speed compression. As a result, it leads to an increase in dynamic material strength. Hakalehto [48] found that when specimen length reduces, more energy can be transmitted by rock specimen and therefore leads to more significant confinement effects. Li and Meng [46] performed numerical modelling and concluded that the influence of end friction on compressive DIF becomes considerable when the friction coefficient is more than 0.2. In a laboratory test, to reduce end friction, lubrication is always applied to grease the interfaces. Zhang et al. [49] concluded specimen with a shorter length is more significantly affected by the end friction effect than a longer specimen during the SHPB test. Gary and Blumenthal [50] also suggested reducing mismatching between specimen and bars ($D_{specimen}=0.8D_{bar}$). Since end friction confinement is inevitable and influence laboratory measured material dynamic strength, Hao et al. [51] conducted comprehensive numerical modelling , and derived an empirical formula to quantify the influence of end friction confinement (Figure 2-2).



(a) (b)

Figure 2-2 Friction effect reported in [51] (a) different L/D ratio with 0.5 friction coefficient; (b) different friction coefficient effect with 0.5 L/D ratio

2.6.3 *Strain rate effect due to material properties*

The mechanism of strain rate effect due to material properties can be attributed to the evolution of cracks and viscosity effect. The mechanism of crack evolution is an important reason for the strain rate effect. Under quasi-static or low-speed impact, only one or a few macro-cracks can be observed because cracks are formed across the weak zone in the specimen. When the specimen is loaded rapidly, there is not enough time for the existing micro-cracks and/or weaker sections in the specimen to extend. Instead, widely spread cracks are formed and forced to propagate through regions of higher resistance, together with a larger number of micro-cracks, they lead to higher failure stress level [52]. The viscosity effect, also known as the Stefan effect [53], is resulted from a thin viscous layer such as water between two layers of material. When an attempt is made to separate these two layers, an opposing force will be created, which is velocity related. In other words, the faster the specimen is loaded, the greater the opposing force will be generated. On a macro-scale, it reflects a higher strength measured on the tested specimens. Some researchers [27, 54] heated or frozen their concrete specimens so as to minimize the influence of free water in specimens, and found the treated concrete specimens were less strain rate sensitive. Another contribution to the strength and stiffness increment under dynamic loading comes from the resistance from the trapped air and water in micro-voids of the specimen [55, 56]. Concrete has about 10% porosity with air and water trapped inside and connected by capillaries. Under static and low-rate loading, these trapped air and water would be slowly pushed out without providing much resistance to the applied load. Under high-speed loading, there is no sufficient time for them to be drained. Therefore, they also resist the applied loads, leading to the enhancement of the material strength.

2.7 Summary

This chapter summarizes existing understandings of the dynamic material properties of brick materials and other construction materials; and reviewed the influence factors to the dynamic properties of materials. It is found that there is a short of sufficient testing data on the dynamic properties of brick materials, which requires more systematic study for more accurate analysis and design of masonry structures.

Existing testing methods for the determination of material mechanical properties at different strain rates are also reviewed. To quantify the tensile properties of brittle materials like brick, split-tensile tests and direct tensile tests are the two of the most predominately employed methods. The latter, direct tensile test, is an ideal testing method in which the tested specimen is under a uniaxial stress state. However, the current specimen fixing method in the dynamic direct tensile test using Split-Hopkinson Tensile Bar (SHTB) system is difficult to achieve, which constrains the practicality of using a dynamic direct tensile test to quantify material dynamic tensile strength at different strain rates. Developing a new clamping method for the dynamic direct tensile test could bring substantial benefits for research of brick and other materials' dynamic tensile properties.

Moreover, previous studies found the tensile strengths determined using these two split-tensile testing method and the direct tensile testing method are not necessarily the same. Some empirical relationships have been developed for static tensile strengths, but there is no proper correlation for them at dynamic states. There is a gap to fill in to properly interpret and correlate the dynamic split-tensile strength and dynamic direct tensile strength.

Chapter 3 Methodology

In this chapter, the methodology employed in this study is presented in detail. Firstly, brick specimens prepared for this study is introduced. Then, the testing methodology for quasi-static and low-speed tests are presented, which are followed by the dynamic compressive testing method using the SHPB system. Last but not least, the quasi-static and dynamic tensile testing methods, including both split-tensile testing and direct tensile testing, are presented. A new clamping method for the dynamic direct tensile test is introduced. And the testing results using the new clamping method is compared and evaluated with conventional specimen fixing methods for dynamic tensile test using Split-Hopkinson Tensile Bar system.

3.1 Sample specifications and preparations (WA clay bricks)

Clay bricks are made by burning a mixture of raw materials (50-60% silica, 20-30% clay, 2-5% lime, less than 7% iron oxide and magnesia) in a kiln. The strengths of bricks are influenced by the composition of raw materials, blending of ingredients, burning temperature, and moulding method etc. In this study, three types of clay bricks, i.e. Copper Brown, Limestone Hues and Common Solid, which are high-strength brick, mid-strength brick, and low-strength brick, were provided by major local brick supplier Midland Bricks with mixtures of Western Australian local clays. One of the most important roles in the mechanical properties of clay bricks is chemical composition plays. XRF analysis is conducted. Table 3-1 summarises the chemical compositions and the material properties of the three types of bricks. It can be observed that the compressive strength of the bricks increases with the ratio of SiO_2 in the mixture as silica is commonly believed to influence composite's compressive strength [57]. 50 mm diameter cylinders were core-drilled from 230 mm × 110 mm × 76 mm solid brick prisms. For the quasi-static and low-speed compressive tests, a 100 mm high cylinder is prepared with a length/diameter ratio of 2:1 according to ASTM recommendation [58]. 50mm diameter by 50mm long cylindrical specimens (length/diameter ratio 1:1) are prepared for the high-speed compressive tests. It is worth noting that there is no established guideline/standard for brick dynamic material testing. Nevertheless, the dimension is selected with the following criterion: 1) specimen diameter is small enough to minimize lateral confinement due to inertia effect; 2) diameter shall be sufficient to represent the uniform material properties from original brick prism; 3) the length/diameter ratio for SHPB test is between 0.5 and 1.0; 4) the length/diameter ratio shall be no less than 1:1 to minimize the influence of end friction in the quasi-static test. The brick specimens are cored and then cut to approximate length. They are then finely grinded with a controlled tolerance of 0.1mm difference for surface flatness. The specimens are then dried in an oven at 40 C° for 48 hours until the extra moisture is removed.

Table 3-1 Material properties of the selected WA bricks

Type of Brick	High strength	Mid strength	Low strength
Density (kg/m^3)	1971.1	1903.5	1960.7
Image			
Fe_2O_3	4.06%	7.87%	9.08%
Al_2O_3	24.92%	20.19%	19.92%
SiO_2	59.43%	57.50%	55.00%
MgO	0.27%	3.08%	4.55%
Na_2O	0.38%	0.83%	0.67%
K_2O	1.90%	1.43%	1.22%
CaO	0.09%	1.01%	1.26%
TiO_2	0.81%	0.87%	0.85%
LOI	7.90%	6.84%	7.04%
Others	0.24%	0.29%	0.33%

Note: Chemical compositions are by volume ratio

It is found the Limestone Hue has the lowest density and shows the medium compressive strength and the lowest tensile strength among the three brick materials tested in this study. The main reasons may be due to 1. Aggregate effect: The limestone Hue is more porous and contains a higher amount of larger aggregates, evidenced from the fragments and the sample surface; 2. Limestone Hue is found to compose more quarts than other brick materials in this study. A recent experimental study conducted by Guo et. al. [59] concluded that the difference in the mix ratio and presence of silica fume in the concrete has varied the performance of material for dynamic resistance. Because the studied brick consist of different sizes and ratios of aggregates and different materials, namely silica, alumina and lime, different strain rate sensitivity and material strength are expected.

3.2 Quasi-static and low-speed compressive tests

The quasi-static and low-speed tests are conducted on a Shimadzu 300 testing system (Figure 3-1). The system has a maximum loading capacity of 300 kN and a maximum loading rate of 500mm/min. The quasi-static test is conducted following ASTM-C39 [58]. The tests are performed at four loading speeds, i.e. 0.01 mm/min, 1mm/min, 60 mm/min and 500 mm/min, which correspond to strain rates of 1.67×10^{-6} /s, 1.67×10^{-4} /s, 0.01 /s and 0.08 /s, respectively. Each test follows a two-stage loading sequence. Take 0.01 mm/min loading speed as an example: the loading platen is controlled at a speed of 1 mm/min until half of the compressive capacity of the specimen is reached, then it is slowed down to 0.01 mm/min until the total fracture of the specimen; the total testing time is around 50 minutes for each test. Three specimens are tested at each loading speed. Lubricants are applied to the contact surfaces of the specimen and platens before the tests to reduce the end friction. Pairs of strain gauges are attached to each specimen to measure axial strain. The strain gauges are installed at the centre of the sample to avoid the end effect on the sample strain measurement. It is worth noting that the vertical displacement of the loading platen could not be used to accurately estimate the axial strain of the brick specimen because the deformation of the loading system itself also contributed to the measurement of the platen displacement. Therefore, strain gage glued on the specimen is recommended for the measurement of stiff and brittle materials like clay brick.

Figure 3-1 Low-speed testing system

3.3 Dynamic compressive test using SHPB

The high-speed compressive test in this study utilized Split-Hopkinson Pressure Bar. SHPB test is normally conducted for defining the material property at a high strain rate. It was firstly introduced by Hopkinson in 1914 and further developed by Davies in 1948 and Kolsky in 1949. As illustrated in Figure 3-2, a Split Hopkinson Pressure Bar normally consists of a striker bar, an incident bar, a transmitter bar and an absorption bar (stop bar). The specimen is sandwiched between the incident bar and the transmitter bar. In a test, the striker bar is launched at a certain velocity and hits the front surface of the incident bar. The impact generates a stress wave in the incident bar, which propagates towards the specimen. By adjusting the velocity of the striker bar, the amplitude of the stress wave can be adjusted. The cross-sectional area of the specimen must often be kept smaller than the bar to achieve the required stress level in the specimen. When the stress wave arrives at the interface between the incident bar and the specimen, due to the impedance mismatch, part of the wave energy is reflected into the incident bar while the rest continues through the specimen. Part of this wave propagates into the transmitter bar. The rest part of the wave is reflected at the interface between the specimen and the transmitter bar, which travels within the specimen back and forth several times, striking a balance until the specimen fails.

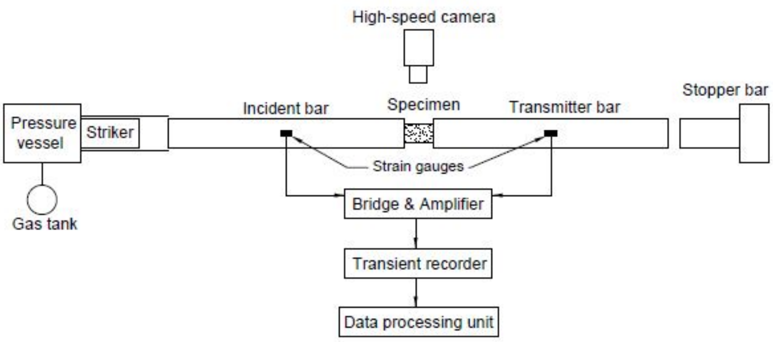


Figure 3-2 Illustration of SHPB system

3.3.1 *One-dimensional wave theory*

The SHPB is based on one-dimensional wave theory. The fundamental assumptions are: a) the bars remain elastic throughout the test; b) specimen deforms homogeneously without premature failure before reaching stress equilibrium; c) inertia effect and end friction are minimized. It is worth noting that the end friction effect could increase material strength [51]. Lubricant is commonly applied to minimize friction between bars and specimen to a negligible level. Once the above assumptions are satisfied, according to the one-dimensional wave theory, the amplitude of the transmitted stress wave is a measure of the stress level in the specimen. In the direct compressive test, the amplitude of the reflected stress is proportional to the strain rate in the specimen. By integrating the strain rate, the strain of the specimen can be determined. Therefore, the stress σ, strain rate $\dot{\varepsilon}$ and strain ε in the compressive test can be expressed as

$$\sigma(t) = \frac{A_e E_e \varepsilon_t(t)}{A_s} \tag{1}$$

$$\dot{\varepsilon}(t) = -\frac{2c_e \varepsilon_r(t)}{L_s} \tag{2}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(\tau) dt \tag{3}$$

where A_e and E_e are the cross-sectional areas and Young's modulus of the elastic bars; ε_t and ε_r are the transmitted and reflected strains in the elastic bars; c_e is the longitudinal bar wave velocity determined by $\sqrt{E_e/\rho_e}$; where ρ_e is the material density of the bar; A_s and L_s are the cross-sectional area and length of the specimen.

3.3.2 *Pulse shaper*

In dynamic testing, obtaining dynamic stress equilibrium and minimising contact stress concentration presents a technical challenge. Brittle materials tend to initiate crack propagation and spalling about the contact area when exposed to a quickly rising shock wave. This reduces the perceived strength of the sample, particularly for heterogeneous specimens such as rocks where microcracks or insipient joints and foliations create local stress raisers. In the traditional SHPB test, the rectangular stress wave with a steep rise generated by the cylindrical striker bar can impose a nonuniform strain rate during the deformation of the rock specimen. Therefore, a gradually ramped stress wave is needed. Comprehensive research into developing techniques to slow down the ramping pulse in the SHPB test has been conducted, which include pacing a thin ductile metallic disc [60, 61] and using a shaped striker bar [62], while the former strategy is more commonly adopted. A copper or aluminium disc is placed in front of the incident bar facing the impact. When the striker is launched, it hits the pulse shaper, which causes it to deform plastically while removing energy from the incident pulse. This results in the square wave rising edge of the incident waveform being turned into a half sinusoidal waveform, which helps to achieve dynamic stress equilibrium in the specimen.

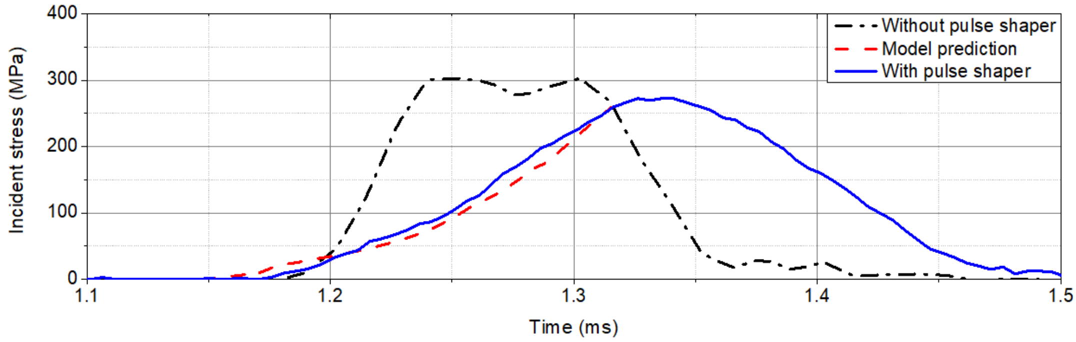


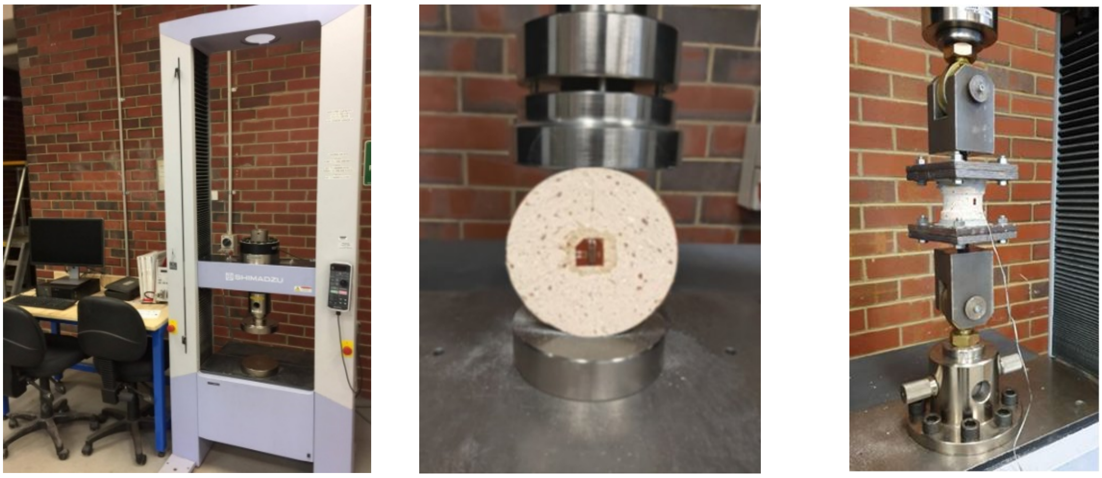
Figure 3-3 Comparisons of incident stress waves with 30mm diameter copper pulse shaper, 300mm long striker at 17m/s

Following the theory by Frew et al. [60], a pulse shaper model based on the values provided for C11000 annealed copper with a striker bar of 300mm long was developed to predict the incident stress history. Figure 3-3 shows the comparison of incident stress wave with and without the pulse shaper and the model prediction. As shown, the pulse shaper elongates the rising edge of the incident wave and provides stress linearity. And the model could also closely predict the incident wave with the pulse shaper. Additionally, during testing, the model provides the opportunity to refine the testing by providing the ability to design loading rates. Nominal pulse shaper sizes of 10mm, 20mm and 30mm were chosen to give a broad range of loading rates.

3.4 Quasi-static and low-speed tensile tests

The indirect split-tensile test is popularly used to determine the tensile strength of brittle materials due to its simplicity in sample preparation and test conduction. Therefore, it is suggested by the ISRM and ASTM as a recommended method for static tensile strength measurement of rocks. Split-tensile tests are conducted at both quasi-static and dynamic states in this study. The quasi-static tests are conducted on a Shimadzu-300 Universal Testing System (Figure 3-4a). Following ASTM-D3967, the brick specimen is clamped in a loading cradle to reduce localized premature failure at the loading point (Figure 3-4b). A pair of strain gauges are glued to the specimen's centre to measure the compressive strain and the split-tensile strain. The applied compressive force is recorded using the inbuilt load cell in the testing system.

The quasi-static direct tensile test is performed using the Shimazu-50 Universal Testing System. The specimen is glued to two end plates which are fixed to the loading clamps. Swivel bearings are installed between the clamp and the loading plate to avoid misalignment and bending damage during the installation process (Figure 3-4c). The tensile force is measured using the inbuilt load cell in the testing system, and strain gauges are glued to the brick specimen to measure the axial strain along the loading direction. The displacement control loading method is used for the direct tensile test, which results in a strain rate of 2.25×10^{-6} /s in the brick specimen for the quasi-static state test. Another quasi-static test with higher loading speed is also carried out, resulting in a strain rate of 2.25×10^{-3} /s.



a) b) c)

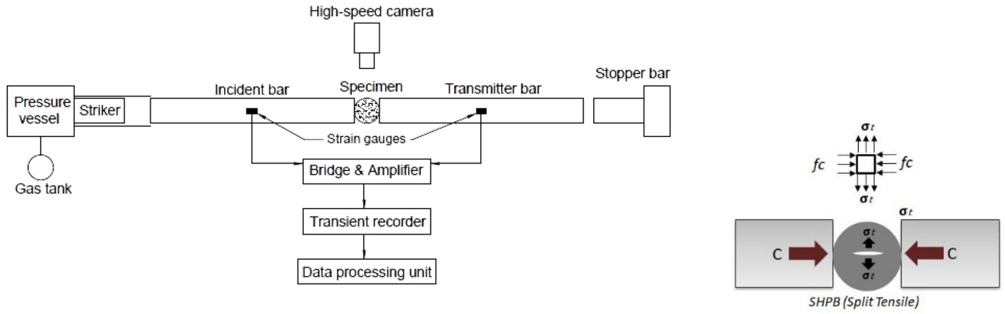
Figure 3-4 Quasi-static tests setup a) Shimadzu-300; b) split tensile test; c) direct tensile test

3.5 High-speed dynamic split-tensile test on SHPB

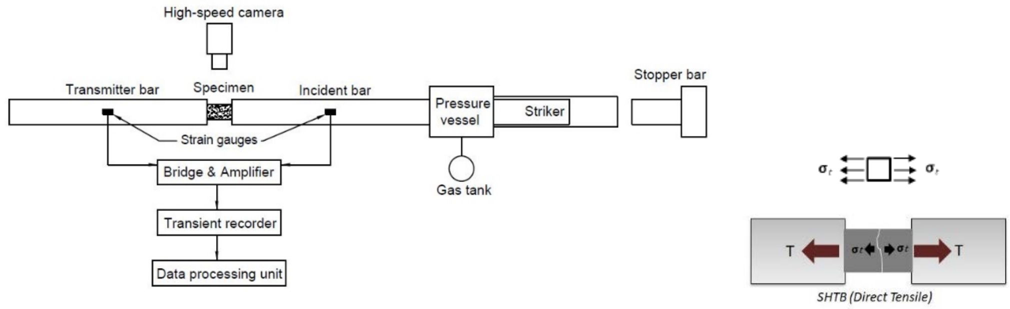
The dynamic split-tensile test is conducted using the SHPB system at Structural Dynamic Laboratory, Curtin University. As illustrated in Figure 3-5a), it comprises of 100 mm diameter incident bar (5000 mm in length) and transmitter bar (3000 mm in length). The striker bar is also 100 mm in diameter and 500 mm in length. The bars are made of high strength tool steel with a density of 7800 kg/m^3 and Young's modulus of 200 GPa. Strain gages are glued to the centres of the incident and transmitter bars to monitor stress waves. A copper pulse shaper is used to help achieve dynamic equilibrium. The copper disc is 3 mm in thickness and 10 mm, 20 mm, or 30 mm in diameter according to different impact speeds used. Figure 3-6a shows the typical stress wave signal recorded in the incident and transmitter bars for the split-tensile test. Dynamic equilibrium is checked to ensure the validity of each high-speed split-tensile test (Figure 3-6b). Eq. (4) gives the formula for calculating the split-tensile strength. Strain gauges are also glued to the specimen's centre in the split-tensile direction to monitor specimen strain. Considering the challenge in predicting the actual strain rate that a specimen experienced in a split-tensile test, most researchers utilize loading rate (unit MPa/s from transmitted stress). Some researchers divide the loading rate with Young's modulus of the tested material to derive the strain rate [18]. In this study, both the loading rate from the transmitted stress and strain rate derived by differentiating the recorded strain time histories measured on the specimen are used to calculate the strain rate.

$$\sigma_t = \frac{2P}{\pi DL} \tag{4}$$

where P is the applied compressive load, D and L are the diameter and length of the specimen.

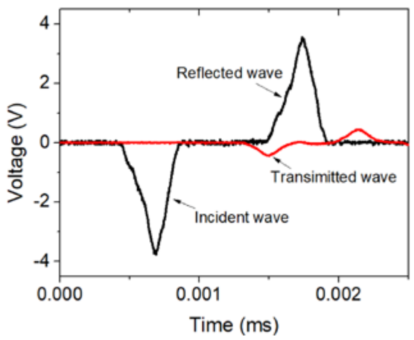


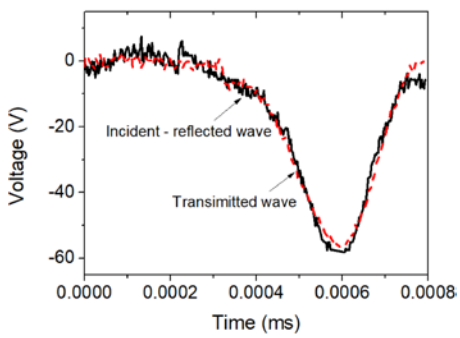
a)



b)

Figure 3-5 Dynamic tensile test setup: a) split-tensile test using SHPB; b) direct tensile test using SHTB system





a) b)

Figure 3-6: a) Typical stress wave signals; and b) dynamic equilibrium of the dynamic split-tensile tests using the SHPB system

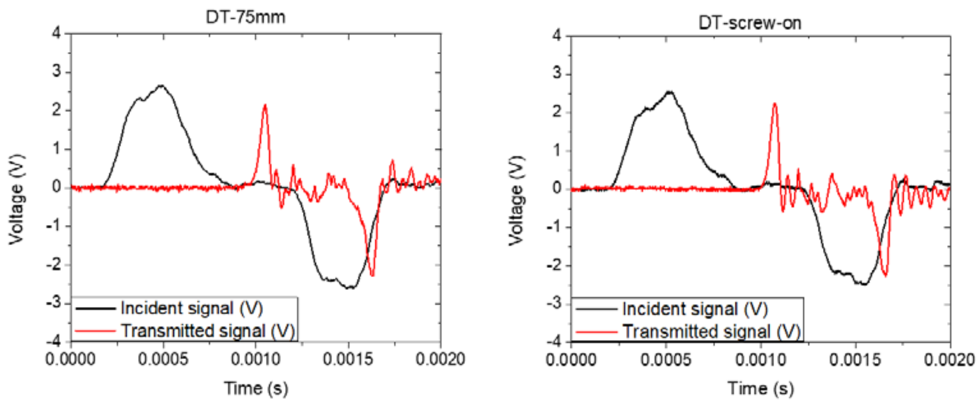
3.6 High-speed dynamic direct tensile test on SHTP

Dynamic direct tensile tests are conducted using the Split-Hopkinson Tension Bar (SHTB). The direct tensile test is straightforward but difficult in practice because the specimen needs to be firmly bonded to the SHTB system using a high strength glue. It takes time for the glue to cure, and after each test, the glue's removal normally requires a mechanical grinding process that could easily damage the incident and transmitter bars. The efficiency of the test is therefore very low. Secondly, to reduce the influence of end effect, dumbbell shape specimen is often used, which nevertheless is very difficult to prepare the specimen, especially when a large number of specimens are tested. Therefore, it is more ideal if cylindrical specimens can be used in lieu of dumbbell shape specimens. To resolve these above challenges, three groups of tests are carried out using different fixing methods and different specimen shapes. Firstly, a group of dumbbell shape specimens are prepared and glued directly to the SHTB system using bi-component epoxy resin (Figure 3-7a). After 48 hours of ambient curing, the specimen is tested, after which it is carefully removed with a steel brush. The whole process takes about three days for each specimen to be tested. Then, a specially designed screw-on clamping device is made, as shown in Figure 3-7b. The clamp is machined using the same tool steel as that of the SHTB bars. The base clamp is firmly fixed to both ends of the SHTB bars, and the brick specimen is glued to the screw-on components of the clamp. After curing, the specimen is carefully screwed onto the SHTB system. The tested specimen can then be easily dismantled from the SHTB, and the system is ready for the next specimen. With this method, the testing efficiency could be greatly improved. It is important to examine the threads' influence for the screw-on clamp to ensure the validity of the SHTB test where stress wave propagate as one-dimensional wave in the bars,. For a third group, the dumbbell shape specimens are replaced with cylindrical brick specimens, as shown in Figure 3-7c. Many previous laboratory test and numerical modelling employed such cylindrical specimens for concrete and rock [7, 59, 63]. The influence of these two different shaped specimens is also examined herein.

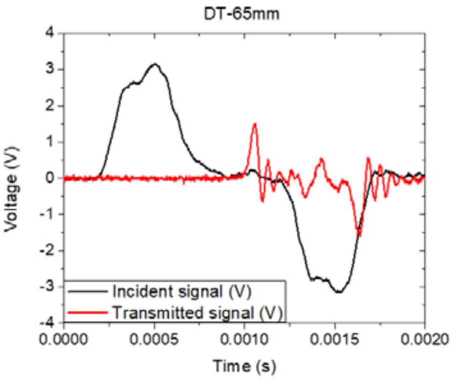
a) b) c)

Figure 3-7 Different testing methods for dynamic direction tensile test using a) direct glue-on method with dumbbell shape specimen; b) screw-on clamps; c) screw-on clamp with cylindrical specimen

Figure 3-8 show the incident and transmitted stress wave signals recorded from direct tensile tests using different specimen shapes and fixing methods. When a similar incident stress wave is generated, the transmitted stress waves recorded for the directly glue-on brick specimen and the screw-on clamping method are very similar. Both the amplitude, the rising time, and the duration for the two types of fixing methods are almost identical, indicating the developed screw-on method could provide very similar performance to the direct glue-on fixing method. Figure 3-9a and b show the dynamic fracturing images of the brick specimens using these two fixing methods. It can be observed that at t = 0.2 ms, cracks are developed in the brick specimens, in which there is no major difference that can be found on the direct glue-on specimen and the screw-on fixed specimen. Figure 3-8c shows the recorded incident and transmitted stress waves for the dumbbell shape specimen. Compared with the cylindrical specimen, similar stress rising rate and stress wave duration are observed. The amplitude of the transmitted wave recorded is smaller, which has not been amplified by the cross-sectional area reduction. Similarly, as shown in Figure 6c, tensile failure occurs with a crack at the mid of the gauge, which demonstrates the validity of the direct tensile test. Through the above comparison, it can conclude that the developed screw-on fixing method could provide a very similar stress wave in the SHTB system as using the directly glue-on method, and the fracturing location of the specimen is not altered either. Also, using a cylindrical shape specimen to replace a dumbbell shape brick specimen would not significantly influence the dynamic direct tensile strength and validity of the test.



a) b)



c)

Figure 3-8 Typical incident and transmitted wave signals recorded in the test with a) directly glue-on cylindrical specimen; b) screw-on clamping method with a cylindrical specimen; c) directly glue-on dumbbell shape specimen

a) b) c)

Figure 3-9 Fracturing images (t=0.2ms) on SHTP tests a) direct glue-on fixing; b) screw-on clamping method; c) glue-on dumbbell shape specimen

3.7 Summary

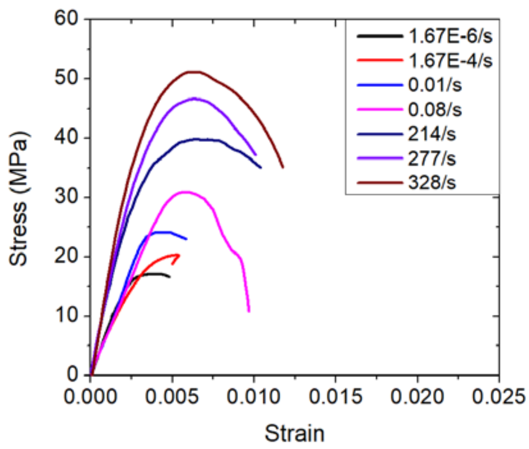
The chapter presents the methodology for determination of the static and dynamic uniaxial compressive and tensile properties of WA clay bricks. Three types of clay bricks using WA local materials are prepared, whose chemical composition is examined. Low-speed uniaxial compressive test is carried out using a Universal Testing System to determine the quasi-static and low-strain rate compressive properties. Dynamic compressive properties are tested using a SHPB system. For the brick tensile properties, both split-tensile test and direct tensile tests are carried out. Focus is made on the dynamic direct tensile test using SHTB system, where conventional direct glue-on method, new screw-on method using dog-bone shape and cylindrical shape specimens are proposed and examined.

Chapter 4 Quasi-static and Dynamic Compressive Properties

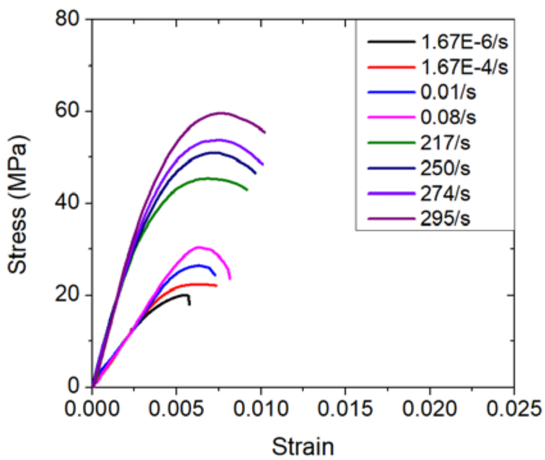
This chapter presents the quasi-static and dynamic compressive properties of clay bricks. Three types of clay bricks are tested under quasi-static state, low-speed and high-speed dynamic states. Brick compressive strength, Young's modulus and ultimate strain at different strain rates are determined. The empirical formula of DIF versus strain rate for each brick is derived.

4.1 Quasi-static and low-speed compressive tests

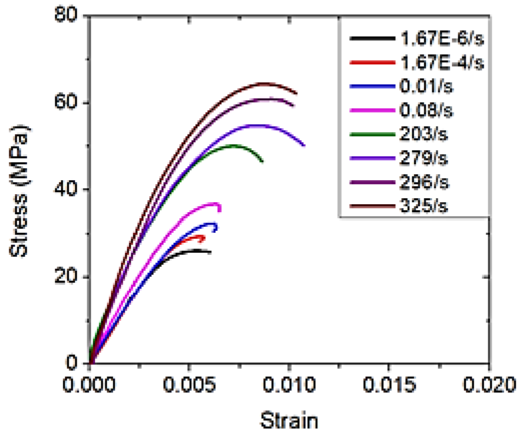
A total of 35 specimens are tested in the low-speed tests. Figure 4-1 shows the representative stress-strain curves (not averaged) of the tested bricks at different strain rates. Under low-speed compression, all three types of bricks exhibit linear elasticity with non-linear behaviour due to specimen damages when it approaches the ultimate strength. An apparent strain rate effect can be observed. The ultimate compressive strengths, failure strain (strain corresponding to ultimate strength) and Young's modulus (Tangent modulus) for all three types of brick materials gradually increased as the loading speeds increased. Table 4-1 summarizes the low-speed test results where H refers to the high strength Copper Brown brick; M refers to the medium strength Limestone Hue brick; and L refers to the low strength Common Solid brick. It can be seen that the specimens have consistent ultimate strengths. The average static ultimate strength is 24.8MPa, 20.4MPa and 18.5MPa for Copper Brown, Limestone Hue and Common Solid bricks, which increase to 37.5MPa, 32.0MPa and 29.2MPa at strain rate 0.08/s.



a) Common Solid



b) Limestone Hue



c) Copper Brown

Figure 4-1 Stress-strain curves at different strain rates

Table 4-1 Summary of quasi-static and low-speed testing results

Test No.	Strain rate (/s)	Compressive strength (MPa)	Ultimate strain	Young's modulus (GPa)
H1	1.67E-06	26.1	0.0053	7.2
H2	1.67E-06	25.9	0.0048	7.4
H3	1.67E-06	22.5	0.0058	7.0
H4	1.67E-04	29.4	0.0055	7.3
H5	1.67E-04	32.9	0.0052	6.8
H6	1.67E-04	26.8	0.0049	7.6
H7	0.01	35.6	0.0053	8.0
H8	0.01	32.4	0.0063	7.2
H9	0.01	34.1	0.0061	7.8
H10	0.08	36.8	0.0065	9.4
H11	0.08	37.2	0.0062	8.2
H12	0.08	38.6	0.0058	7.6
M1	1.67E-06	20.1	0.0053	6.7
M2	1.67E-06	21.0	0.0056	6.2
M3	1.67E-06	20.3	0.0057	6.1
M4	1.67E-04	24.8	0.0061	7.2
M5	1.67E-04	24.6	0.0059	6.9
M6	1.67E-04	22.4	0.0057	6.6
M7	0.01	26.5	0.0067	6.2
M8	0.01	26.2	0.0063	6.5
M9	0.01	27.2	0.0066	7.5
M10	0.08	33.3	0.0066	7.5
M11	0.08	30.4	0.0068	6.8
M12	0.08	32.2	0.0062	7.6
L1	1.67E-06	17.1	0.0049	6.9
L2	1.67E-06	20.6	0.0043	7.2
L3	1.67E-06	17.8	0.0045	7.6
L4	1.67E-04	20.3	0.0053	6.9
L5	1.67E-04	16.9	0.0048	7.3
L6	1.67E-04	17.8	0.0046	6.9
L7	0.01	25.4	0.0053	7.7
L8	0.01	24.2	0.0048	6.6
L9	0.01	22.8	0.0049	7.0
L10	0.08	30.9	0.0056	7.3
L11	0.08	27.4	0.0049	7.8

4.2 Dynamic tests on SHPB system

The high-speed compressive tests are conducted on the SHPB testing system at the Structural Dynamics Laboratory in Curtin University (Figure 4-2). The testing system comprises a 100 mm diameter incident bar (5000 mm in length) and a transmitted bar (3000mm in length). The striker bar is also 100mm in diameter and 500mm long. The bars are made of high strength tool steel with a density of 7800kg/m^3 and Young’s modulus of 200GPa. Strain gages are glued to the centres of the incident and transmitter bars to monitor stress waves.

Figure 4-2 Spilt-Hopkinson Pressure Bar system

4.2.1 *Signals received and stress equilibrium*

The vessel pressure to launch the striker bar is manually controlled to vary from 0.1MPa to 0.3MPa, which results in the strain rate of the specimen varying from approximately 190/s to 340/s. Figure 4-3 shows the typical stress wave signals recorded from incident and transmitter bars during a test. A pulse shaper is utilized and placed between the striker bar and the incident bar for each test to assist the dynamic compressive tests on brittle material and get consistent test results. Dynamic equilibrium is carefully checked, as illustrated in Figure 4-4 a-c for each type of brick materials.

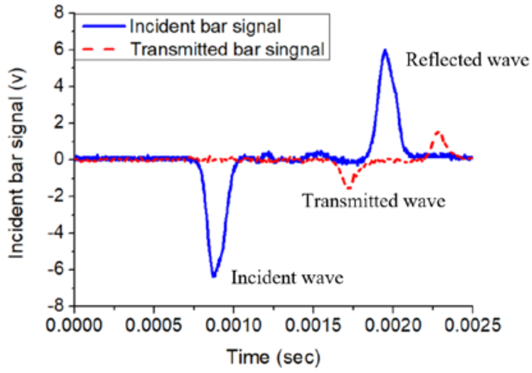
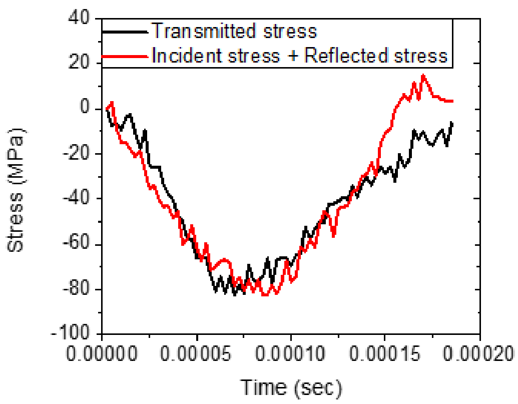
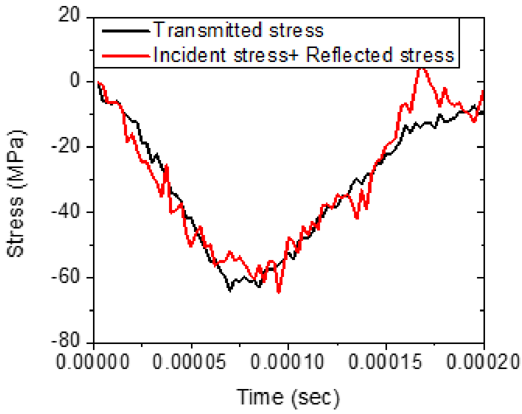


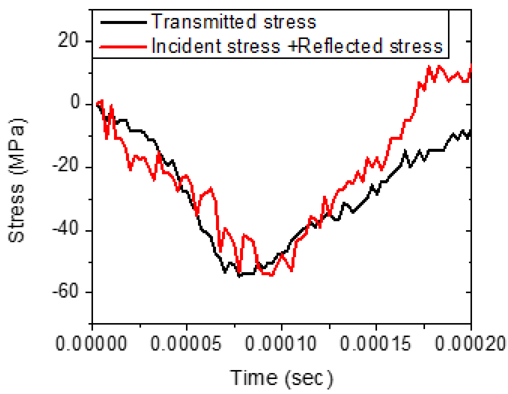
Figure 4-3 Typical stress wave signals recorded in the incident and transmitter bars



a) Copper Brown (CB4-0.3)



b) Limestone Hue (LH4-0.3)



c) Common Solid (CS8-0.26)

Figure 4-4 Dynamic equilibriums for three typical specimens

4.2.2 Dynamic tests results

Figure 4-1 shows the stress-strain curves of different strain rates in the high-speed compressive tests, it can be found that the stress-strain curves have similar trends as those corresponding to the low-strain rates, i.e., under uni-axial compression, the tested clay brick behaves linear elastic at the beginning which exhibits non-linearity when it approached its ultimate strength. A clear strain rate effect can be found on the stress-strain curves. As strain rate increases, higher ultimate compressive strength can be found on the brick materials. For instance, the compressive strength of Common Solid brick increases from 37.7 MPa at a strain rate of 198 /s to 51.2 MPa at a strain rate of 328 /s, indicating an increment of 35.8 % in brick strength. Similarly, for Limestone Hue brick, the compressive strength increases by 36 % from 45.4MPat at a strain rate of 217 /s to 61.7 MPa at a strain rate of 337 /s. The slope of the initial stress-strain curves also increases as the strain rate increased, indicating Young’s modulus also changes with strain rate. Typically for Common Solid brick, the modulus increases from 12.3GPa at 198 /s to 16.2GPa at 328 /s, reflecting a 31.7 % increment in brick modulus. Table 4-2 to 4-4 summarizes the test results of the three types of bricks in the high-speed compressive tests.

Table 4-2 Summary of high-speed test results for Copper Brown brick

Test No.	Strain rate (/s)	Ultimate strength (MPa)	Ultimate strain (mm/mm)	Young's modulus (GPa)	DIF (strength)	DIF (strain)	DIF (modulus)
CB-01	203	50	0.00712	11.6	2.01	1.34	1.62
CB-02	212	52	0.00761	12.3	2.1	1.43	1.71
CB-03	214.7	44.9	0.00834	10.3	1.81	1.57	1.43
CB-04	219	53.2	0.00831	12.7	2.14	1.56	1.77
CB-05	224.3	52.8	0.00671	13.4	2.13	1.26	1.87
CB-06	234.1	57.8	0.00764	16	2.33	1.44	2.22
CB-07	236.6	55	0.00725	15.4	2.22	1.37	2.14
CB-08	239.8	56.9	0.00648	12.9	2.29	1.22	1.79
CB-09	243.4	58	0.00839	15	2.34	1.58	2.09
CB-10	250	54.6	0.00649	15	2.2	1.22	2.09
CB-11	268	61.1	0.0072	12.9	2.46	1.36	1.8
CB-12	271.7	45.7	0.00824	14.1	1.84	1.55	1.97
CB-13	273.1	55.6	0.00724	13.4	2.24	1.36	1.86
CB-14	275.7	46.3	0.00732	13.1	1.87	1.38	1.82
CB-15	277	62	0.00733	14.6	2.5	1.38	2.02
CB-16	278.9	54.8	0.00876	13.7	2.21	1.65	1.9
CB-17	296.2	61	0.0085	14.3	2.46	1.6	1.99
CB-18	301.7	65	0.00843	15.5	2.62	1.59	2.15
CB-19	308.6	56.4	0.00677	12	2.27	1.27	1.67
CB-20	311	60.2	0.006	17.6	2.42	1.13	2.45
CB-21	313.2	47.9	0.00721	13.8	1.93	1.36	1.92
CB-22	315.8	65.4	0.00823	17.8	2.63	1.55	2.47
CB-23	322.1	67.5	0.00749	17.3	2.72	1.41	2.4
CB-24	325	64.5	0.00876	16.9	2.6	1.65	2.35
CB-25	326.7	56.2	0.00769	14.2	2.26	1.45	1.97

CB-26	333	58	0.00874	15.2	2.34	1.65	2.12
CB-27	333	65.1	0.00852	17.8	2.62	1.6	2.48
CB-28	335.4	63.8	0.00867	16.4	2.57	1.63	2.28

Table 4-3 Summary of high-speed test results for Limestone Hue brick

Test No.	Strain rate (/s)	Ultimate strength (MPa)	Ultimate strain (mm/mm)	Young's modulus (GPa)	DIF (strength)	DIF (strain)	DIF (modulus)
LH-01	201	46.7	0.00667	10.1	2.28	1.2	1.6
LH-02	201.6	47.5	0.00759	11.4	2.32	1.37	1.8
LH-03	207.5	52.9	0.00792	12.3	2.59	1.43	1.94
LH-04	213	50.7	0.00769	14	2.48	1.39	2.21
LH-05	217.1	45.4	0.00686	12.1	2.22	1.24	1.92
LH-06	218	50.1	0.00805	12.3	2.45	1.45	1.95
LH-07	226.4	45.9	0.00779	11.2	2.24	1.4	1.76
LH-08	234.5	46.5	0.00872	11.7	2.27	1.57	1.85
LH-09	248.7	46.3	0.00773	12.8	2.26	1.39	2.02
LH-10	250	52.3	0.00713	14.2	2.55	1.29	2.24
LH-11	261	56.6	0.00622	13.7	2.77	1.12	2.17
LH-12	261.6	50.1	0.00765	11.5	2.45	1.38	1.82
LH-13	263	55.4	0.0064	15.2	2.71	1.15	2.4
LH-14	263.1	47.4	0.00819	13	2.31	1.48	2.05
LH-15	273.5	48	0.00663	14.3	2.34	1.2	2.25
LH-16	274	53.6	0.00724	11.2	2.62	1.31	1.77
LH-17	278.8	59.5	0.00887	15.8	2.9	1.6	2.49
LH-18	295.4	59.6	0.00729	12.6	2.91	1.31	2
LH-19	299.5	49.1	0.00832	15.2	2.4	1.5	2.39
LH-20	308.9	52.9	0.00823	15	2.58	1.48	2.37
LH-21	315.3	58.5	0.00918	13.1	2.86	1.66	2.07
LH-22	316	49.3	0.00648	16.8	2.41	1.17	2.65
LH-23	318.5	56	0.00864	14.8	2.74	1.56	2.34
LH-24	324	52.5	0.00839	14	2.57	1.51	2.21
LH-25	325.3	53	0.0082	15.3	2.59	1.48	2.42
LH-26	330.2	51.1	0.00804	13.8	2.5	1.45	2.17
LH-27	330.3	56.7	0.00929	16.6	2.77	1.68	2.62
LH-28	336.2	50.6	0.00844	15.2	2.47	1.52	2.41
LH-29	337	61.7	0.00557	14.4	3.01	1.00	2.27

Table 4-4 Summary of high-speed test results for Common Solid brick

Test No.	Strain rate (/s)	Ultimate strength (MPa)	Ultimate strain (mm/mm)	Young's modulus (GPa)	DIF (strength)	DIF (strain)	DIF (modulus)
CB-01	195.4	41.4	0.00684	13.8	2.24	1.49	1.92
CB-02	198	37.7	0.00745	12.3	2.04	1.63	1.69
CB-03	210.3	38.6	0.00542	12.5	2.09	1.18	1.73
CB-04	214	39.8	0.00715	13.9	2.15	1.56	1.92
CB-05	217.7	46.4	0.00558	12.9	2.51	1.22	1.79
CB-06	231.6	46.3	0.00617	12.8	2.51	1.35	1.77
CB-07	244.3	47.6	0.00767	11.3	2.57	1.68	1.57
CB-08	257.2	44	0.00646	14.3	2.38	1.41	1.98
CB-09	259	44.3	0.0064	14.5	2.4	1.4	2
CB-10	268	38.4	0.00507	12.5	2.08	1.11	1.72
CB-11	269.6	38.8	0.00609	14.2	2.1	1.33	1.96
CB-12	270	44.7	0.00551	14.9	2.42	1.2	2.06

CB-13	273.2	50	0.00699	13.4	2.7	1.53	1.86
CB-14	273.8	48.3	0.00618	14.8	2.62	1.35	2.04
CB-15	277	46.6	0.00619	14.4	2.52	1.35	1.99
CB-16	278	49.3	0.00561	16.7	2.67	1.23	2.31
CB-17	288.3	37.4	0.00482	14.1	2.03	1.05	1.96
CB-18	292.3	43.4	0.00533	13.3	2.35	1.16	1.84
CB-19	292.8	51.5	0.00774	15.7	2.79	1.69	2.17
CB-20	300.6	38.5	0.00568	13.8	2.08	1.24	1.92
CB-21	311	40.2	0.005	13.2	2.17	1.09	1.82
CB-22	311.3	44.4	0.00618	15.3	2.4	1.35	2.12
CB-23	315	50.9	0.00766	16.1	2.76	1.67	2.23
CB-24	320.3	40.1	0.00488	14.8	2.17	1.07	2.04
CB-25	321.7	40.4	0.0049	15.2	2.19	1.07	2.11
CB-26	323	50.8	0.00634	14.9	2.75	1.39	2.06
CB-27	323.1	44.4	0.00611	16.6	2.4	1.33	2.3
CB-28	328.2	51.2	0.00638	16.2	2.77	1.39	2.23

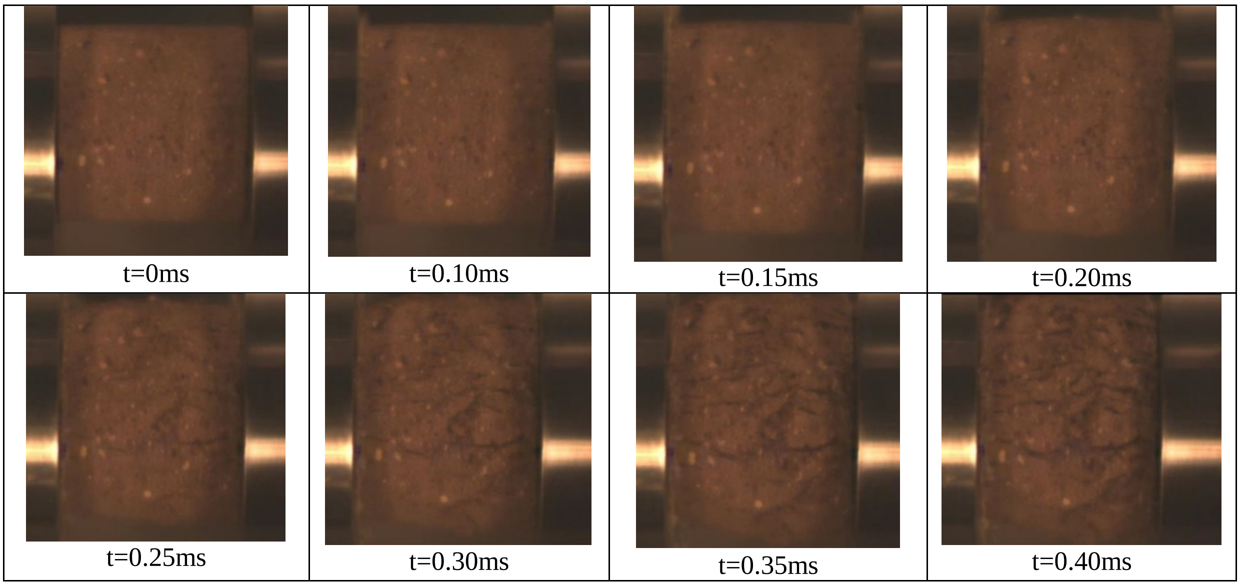
4.3 Dynamic fracturing process

A high-speed camera (Fastcam SA-Z by Photron®) is used to film the dynamic fracturing process of the brick specimens. The filming rate is 40kHz. The typical fracturing process of each type of brick specimen is shown in * Label on the specimen does not represent the test No.

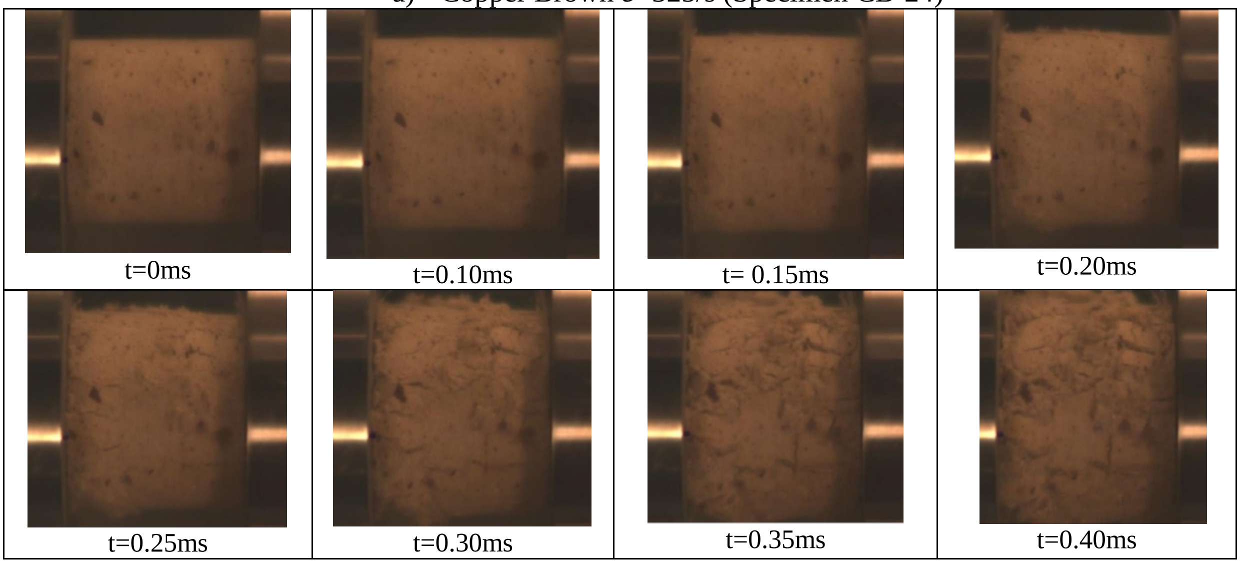
Figure 4-5a-c. Typically for the Copper Brown brick (specimen CB-24) in* Label on the specimen does not represent the test No.

Figure 4-5a it can be observed that shortly after the stress wave arrives at the specimen, it travels back and forth within the specimen. The specimen expands around the centre of the cylinder at t = 0.15 ms. Surface cracks can be observed initiating at the centre of the specimen at t = 0.25ms, which quickly extends towards both ends of the specimen (t = 0.3 ms). More and more cracks are developed, leading to the total burst of the specimen at t = 0.4ms. A similar fracturing process can be found on the other two types of brick specimens. As can be observed in * Label on the specimen does not represent the test No.

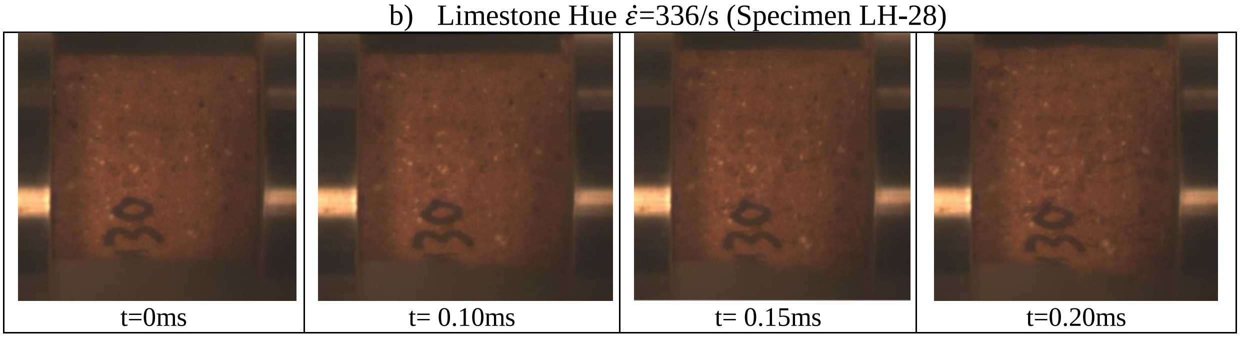
Figure 4-5b for the Limestone Hue brick (specimen LH-28), at t = 0.15 ms, the centre of the specimen begins to expand laterally. At t = 0.2 ms, apparent lateral expansion of the specimen can be found. Surface cracks can be observed at t = 0.25 ms. And the number of cracks increases rapidly, leading to the ultimate failure of the specimen at t = 0.4 ms. At a similar strain rate (323 /s), the Common Solid brick has cracks initiated from the right side of the specimen at t = 0.20 ms, which develops and extends through the specimen at t = 0.30 ms. More cracks are formed quickly, which lead to the total fracture of the specimen at around t = 0.4 ms. In a comparison of the three types of bricks, it can be observed that at similar strain rates, because of lower strength and resistance, crack initiates slightly earlier on the Common Solid bricks, while the difference between the Limestone Hue and Copper Brown bricks cannot be distinguished by visual observation.

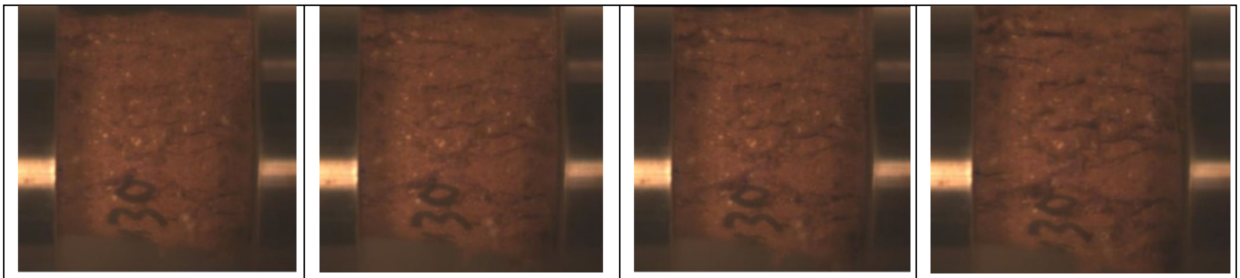


a) Copper Brown $\dot{\varepsilon}$=325/s (Specimen CB-24)



b) Limestone Hue $\dot{\varepsilon}$=336/s (Specimen LH-28)





t=0.25ms t=0.30ms t=0.35ms t=0.40ms

c) Common Soild $\dot{\varepsilon}$=323/s (Specimen CS-26)
* Label on the specimen does not represent the test No.

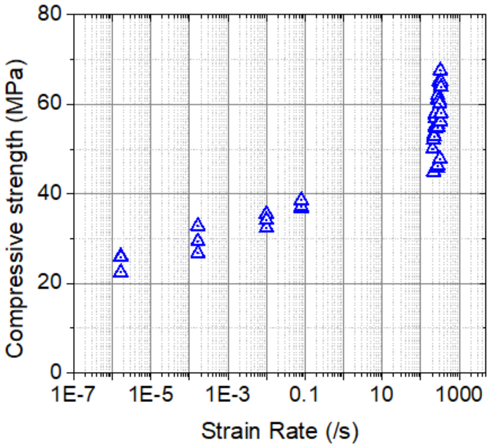
Figure 4-5 Dynamic fracturing process of brick specimens

In figure 4-6a-c shows the typical brick fragments from the tested specimens at different strain rates. It is clear that as loading speed (strain rates) increases, the brick specimens break into more numbers but smaller pieces of fragments. For instance, under quasi-static compression, the Copper Brown brick cylinder breaks into three large pieces with typical shear cracks under uni-axial compression. As the strain rate increases to 0.08/s, more fragments have resulted, and the specimen breaks into a few smaller pieces. When strain rate increases to 203/s, the compressive stress wave shatters the brick specimen into numerous smaller brick shards and fine aggregates. At the largest strain rate of 325/s achieved in this test, only fine fragments are collected after the test. Similar observations can be found on the Limestone Hue and Common Solid brick specimens as well. The observation indicates that more cracks and, therefore finer fragments are produced when the brick specimens are under a higher compressive stress wave. Previous tests by Hao and Tarasov [42] on clay bricks and Chen et al. [64] on concrete, mortar and cement also reported similar observations on the tested specimens. This is because, under low-speed compression, cracks initiate and develop from existing defects within the brick material matrix. As loading speed increases, there is not sufficient time for these cracks to extend and grow. Instead, the stress wave propagates through the high resistance/strength particles resulting in more micro-cracks. More associated energy is therefore consumed, which leads to higher compressive strengths of brick material at higher strain rates.

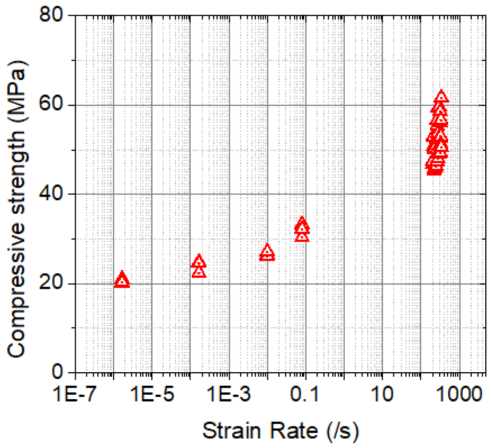
Figure 4-6 Brick fragments at different strain rates

4.4 Strain rate effects on compressive strength

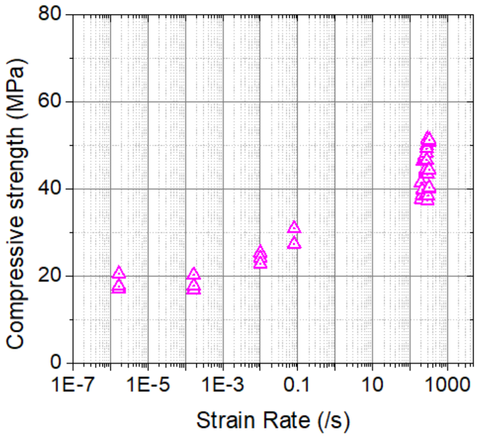
The uniaxial compressive tests in Section 3 show an apparent strain rate effect on the three types of clay bricks. The quasi-static and dynamic strengths at different strain rates are summarized and plotted in Figure 4-7. For all three types of clay bricks, it is clear that the compressive strength increases with the applied strain rate. Under low-speed compression, the brick strength increases steadily as the loading rate increases. A significant increase in brick strength can be found when they are under high-speed compression. When the strain rate is above 100 /s, the compressive strengths of the tested brick increases quickly as the strain rate increases. For instance, at 10^{-6} /s, the averaged compressive strength of the Copper Brown brick is about 25MPa, whose strength increases steadily to nearly 40 MPa at 0.1 /s. At a strain rate of about 100/s, the compressive strength increases to about 45MPa, and further increases to approximately 70MPa at 300/s. Similarly, for Limestone Hue brick, the averaged compressive strength is about 20MPa under quasi-static compression. At strain rate 0.1/s, the compressive strength increases to about 30MPa. At a strain rate of about 300/s, the compressive strength rises to about 60MPa. A similar trend can also be observed on the Common Solid brick.



a) Copper Brown



b) Limestone Hue

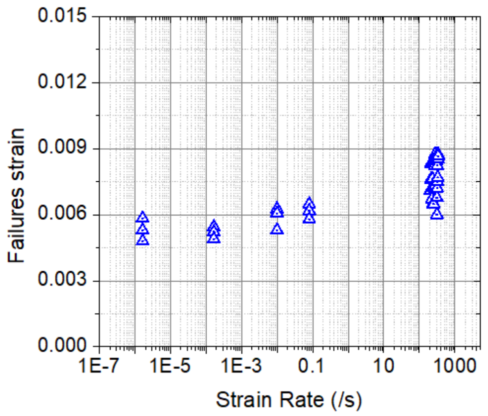


c) Common Solid

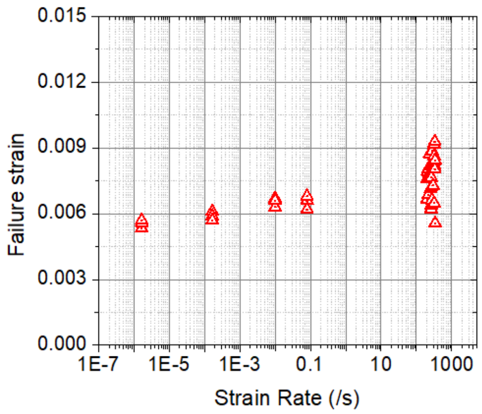
Figure 4-7 Compressive strength vs. strain rate

4.5 Strain rate effect on failure strain

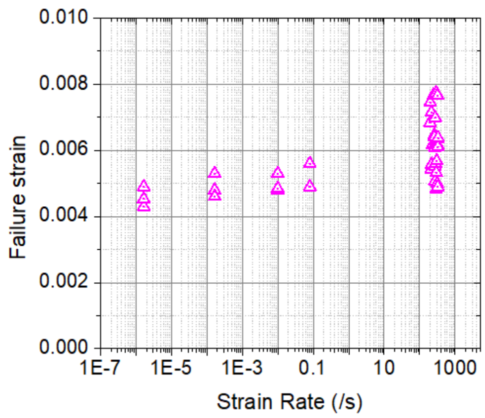
Figure 4-8 shows the failure strains to correspond to the ultimate compressive strengths as a function of strain rate for each type of brick materials. For the Copper Brown brick, the averaged failure strain is between 0.005 and 0.0065 in the low-speed tests with a steady increasing trend. In the high-speed compression range, the failure strain increases rapidly with the applied strain rates. A similar trend on failure strain can be found for the Limestone Hue and Common Solid bricks. For the Limestone Hue brick, the failure strain increases from about 0.005 under static-state to about 0.007 at a strain rate of about 0.1/s in the low-speed regime. It increases a lot more quickly from 0.007 to 0.009 with strain rate (between 200/s and 350/s) under high-speed compression. For the Common Solid brick, the averaged failure strain increases from 0.0045 under a quasi-static state to about 0.005 at strain rate 0.1/s, and then increases quickly from about 0.006 at the strain rate of about 190/s to about 0.008 at strain rate 350/s.



a) Copper Brown



b) Limestone Hue

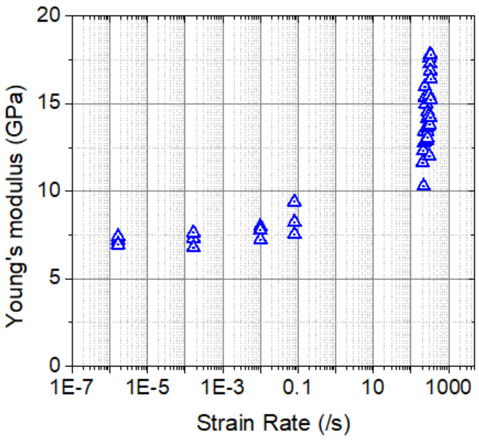


c) Common Solid

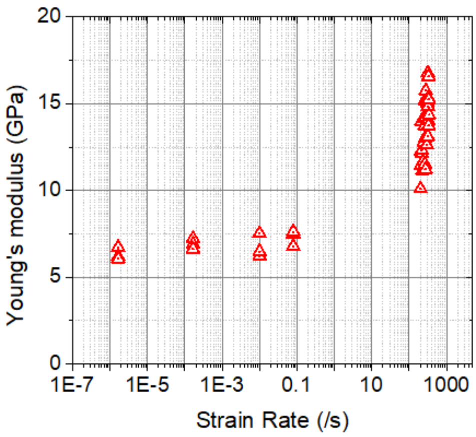
Figure 4-8 Failure strain vs. strain rate

4.6 Strain rate effect on Young’s modulus

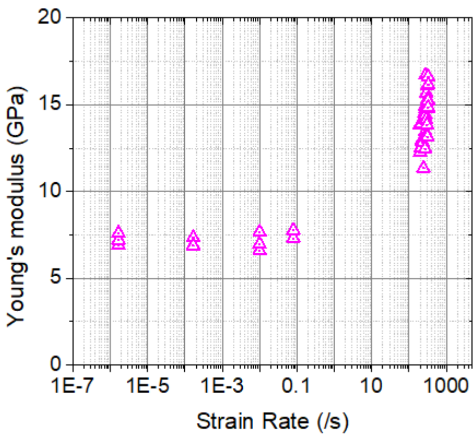
The Young’s moduli of the three types of bricks show an obvious increase especially as the loading speed increases from low-speed compression to high-speed compression. The relation between Young’s modulus and the corresponding strain rate for each type of brick materials are plotted in Figure 4-9. As can be observed under low-speed compression Young’s moduli of the Limestone Hue and Copper Brown bricks both increases with strain rate, while that for the Common Solid brick appears to be less sensitive to strain rate effect. When the strain rate is higher than 100/s, apparently increasing Young’s modulus with strain rate can be observed for all three types of bricks.



a) Copper Brown



b) Limestone Hue



c) Common Solid

Figure 4-9 Young’s modulus vs. strain rate

4.7 Dynamic increase factor and empirical formula

Dynamic increase factor (DIF) is derived by using the dynamic compressive strength divided by the averaged quasi-static compressive strength for each type of brick, respectively. Available testing data reported by other researchers on brick material are also included for analysis and comparison. As shown in Figure 4-10, it is clear that the measured DIF of brick compressive strength increases with strain rate. Under low-speed compression, DIF increases gradually from 1.0 at a quasi-static state to about 1.5 at a strain rate of 0.1/s. A previous test by Hao and Tarasov [42] concluded a DIF of 1.29 for clay brick at a strain rate of 0.1/s, which is 16% lower than those in this study. In the high-speed compression region, the DIF of brick strength increases quickly from about 1.7 at a strain rate of about 100/s to nearly 3.0 at a strain rate of 300/s. Previous testing results in reference [42, 43] covers medium strain rate region up to 200/s, whose DIF for strain rate from 100/s to 200/s are much higher than those from this study. There are a few possible reasons for the above difference. Firstly, the dimension of the specimens in the previous studies adopted a length/diameter ratio of 2:1, while that in this study is 1:1. The longer specimen in the previous test could lead to a more significant axial inertia effect, especially when the strain rate is high. Secondly, probably different types of bricks were tested. The static compressive strength of the brick in [42] was about 45MPa, which is much higher than any type of bricks tested in this study, indicating different chemical compositions (likely higher ratio of SiO_2) and manufacture processes. Since the chemical composition was not examined in the previous studies, it is difficult to compare the influence of this aspect. Last but not least, experimental studies on concrete found that higher strength concrete exhibits less significant strain rate effect as compared with lower strength concrete, which is also recommended by CEB [65] for practice. Some researchers explained this phenomenon as higher-strength concrete breaks with a larger number of aggregate failure than lower-strength concrete under static compression. Since part of the dynamic increment to concrete strength is gained through the propagation of cracks though the stronger aggregate, the proportionate increase in strength should be greater for the weaker concrete [66]. It is likewise for clay brick which is also brittle material comprised of a mixture of void, hard and soft composites. The DIFs derived from reference [41] is much lower than those from this study or previous experimental data. Larcher et al. [41] attributed the insignificant strain rate effect to low humidity in his brick specimens. Because the water in the micro-pores of brick specimens vapoured during the burning process, the influence of the water-induced strain rate effect, therefore, becomes insignificant. In comparison, the brick specimens in this study were all water cut, grinded and under-through oven drying at controlled humidity. Water in micro-pores still exists, which therefore leads to a more significant dynamic increase effect.

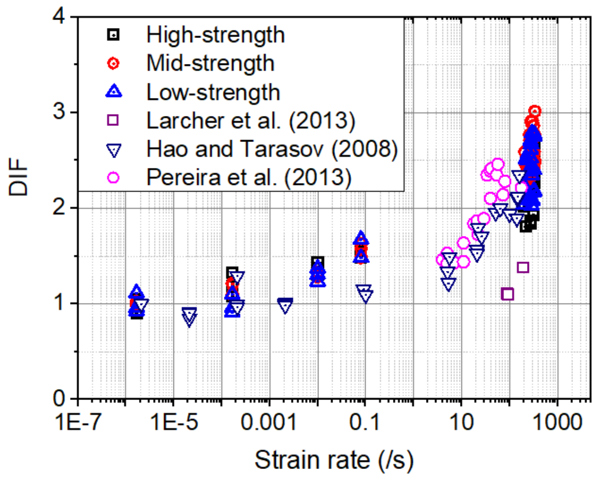


Figure 4-10 DIF of compressive strength vs. strain rate

From the testing data, the DIF of each type of brick materials' compressive strength, ultimate strain and Young's modulus are derived as a function of strain rate and shown in Figure 4-11, Figure 4-12, and Figure 4-13 respectively. The best-fitted equation of compressive strength is:

Copper Brown brick:

$DIF_{HS,fc} = 0.107 \log(\acute{\varepsilon}) + 1.606$ when $1.0\text{^-}6 \le \acute{\varepsilon} \le 168$

$DIF_{HS,fc} = 2.132 \log(\acute{\varepsilon}) - 2.906$ when $168 \le \acute{\varepsilon}$ (5)

Limestone Hue brick:

$DIF_{MS,fc} = 0.110 \log(\acute{\varepsilon}) + 1.605$ when $1.0\text{^-}6 \le \acute{\varepsilon} \le 99$

$DIF_{MS,fc} = 1.633 \log(\acute{\varepsilon}) - 1.434$ when $99 \le \acute{\varepsilon}$ (6)

Common Solid brick:

$DIF_{LS,fc} = 0.114 \log(\acute{\varepsilon}) + 1.567$ when $1.0\text{^-}6 \le \acute{\varepsilon} \le 76$

$DIF_{LS,fc} = 1.097 (\acute{\varepsilon}) - 0.281$ when $76 \le \acute{\varepsilon}$ (7)

where $\acute{\varepsilon}$ is the strain rate.

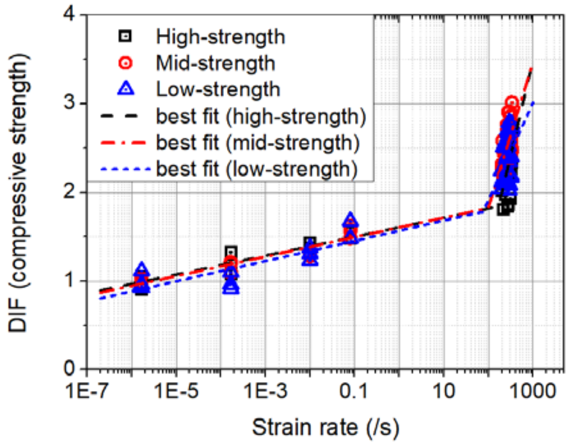


Figure 4-11 DIF of compressive strength vs strain rate

For the ultimate strain:

Copper Brown brick:

$DIF_{HS,us}$ = 0.012 log (ἑ) + 1.072 when 1.0^-6 ≤ ἑ ≤ 200

$DIF_{HS,us}$ = 1.781 log (ἑ) – 2.998 when 200≤ ἑ (8)

Limestone Hue brick:

$DIF_{MS,us}$ = 0.011 log (ἑ) + 1.081 when 1.0^-6 ≤ ἑ ≤ 200

$DIF_{MS,us}$ = 1.915 log (ἑ) – 3.300 when 200 ≤ ἑ (9)

Common Solid brick:

$DIF_{LS,us}$ = 0.013 log (ἑ) + 1.093 when 1.0^-6 ≤ ἑ ≤ 200

$DIF_{LS,us}$ = 1.784 (ἑ) – 2.984 when 200 ≤ ἑ 10)

where ἑ is the strain rate.

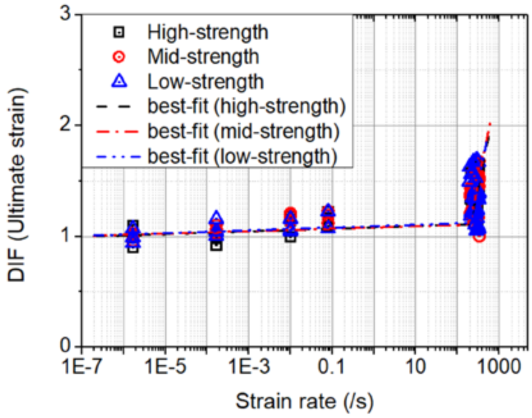


Figure 4-12 DIF of ultimate strain vs strain rate

For the Young's modulus:

Copper Brown brick:

$$DIF_{HS,E} = 0.029 \log(\acute{\varepsilon}) + 1.145 \quad \text{when } 1.0\text{^-}6 \leq \acute{\varepsilon} \leq 132$$
$$DIF_{HS,E} = 2.520 \log(\acute{\varepsilon}) - 4.126 \quad \text{when } 132 \leq \acute{\varepsilon} \qquad (11)$$

Limestone Hue brick:

$$DIF_{MS,E} = 0.026 \log(\acute{\varepsilon}) + 1.162 \quad \text{when } 1.0\text{^-}5 \leq \acute{\varepsilon} \leq 117$$
$$DIF_{MS,E} = 2.564 \log(\acute{\varepsilon}) - 4.088 \quad \text{when } 117 \leq \acute{\varepsilon} \qquad (12)$$

Common Solid brick:

$$DIF_{LS,E} = 0.004 \log(\acute{\varepsilon}) + 1.009 \quad \text{when } 1.0\text{^-}5 \leq \acute{\varepsilon} \leq 76$$
$$DIF_{LS,E} = 1.728 \log(\acute{\varepsilon}) - 2.236 \quad \text{when } 76 \leq \acute{\varepsilon} \qquad (13)$$

where $\acute{\varepsilon}$ is the strain rate.

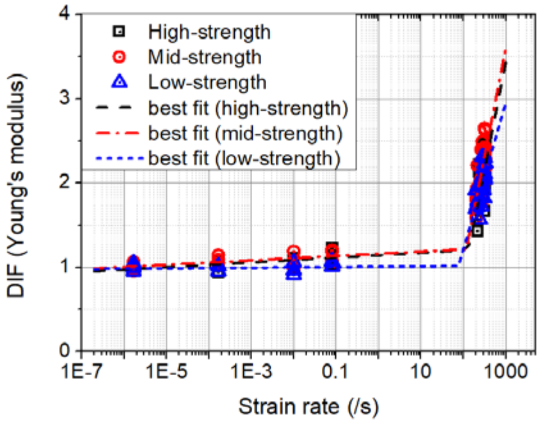


Figure 4-13 DIF of Young's modulus vs strain rates

Through comparison on the best-fit curves for compressive strength, it can be found that the trends for mid-and Copper Brown bricks are very similar. In comparison, Common Solid brick is slightly less strain rate sensitive in the low strain rate range. A very similar trend for the ultimate strain can be found for all three types of bricks. Similar best-fit curves of Young's modulus can also be found for Limestone Hue and Copper Brown bricks. For Common Solid bricks, the influence of strain rate is less sensitive in the low strain rate regime. The above comparisons indicate that the dynamic increase in brick compressive strength is closely correlated to the increase of Young's modulus and ultimate strain. It should be noted that the turning point for the best-fit curves above is all empirical based on test results. More dynamic tests covering intermediate strain rate between 0.1/s to 200/s are needed for providing more accurate derivation of DIF relation with strain rate.

4.8 Summary

In this chapter, the dynamic material properties of three types of WA clay bricks are investigated. Both low-speed and high-speed uniaxial compression tests were performed covering the strain rate range from $1.67e^{-5}$/s to 0.08/s and 190/s to 340/s. The test results revealed the strain rate effect on the compressive strength, ultimate strain and Young’s modulus. In the low-strain rate range, the strain rate effect was found less significant, which became more significant in the high-strain rate regime. As loading speed increases, more number of fractured brick pieces and finer fragments were collected after the tests. It can be explained that higher impact energy was absorbed by the specimen and resulted in more numbers of finer fragments during the high strain rate test. Empirical formulae of DIFs for compressive strength, ultimate strain and Young’s modulus with the strain rate for the three types of bricks are derived and presented, which can later be used to model masonry structure under dynamic loads. Comparisons with other researcher’s dynamic tests on bricks found different DIF relations with strain rates, indicating the DIF sensitivity is dependent on the material composition and contents of brick material

Chapter 5 Quasi-Static and Dynamic Tensile Mechanical Properties

This chapter presents the tensile properties of clay bricks. Both direct tensile test and split-tensile test are carried out at quasi-static and dynamic states. The tensile properties determined using the split-tensile testing method and direct tensile testing method are compared and evaluated. Correlation between the direct tensile strength and split-tensile strength is made. The tensile strength, corresponding failure strain and Young's modulus at different strain rates are quantified. With available testing results, the empirical formula of DIF for brick tensile strengths at different strain rates is derived.

5.1 Split- tensile tests

5.1.1 Quasi-static Split tensile test

The indirect split-tensile test is popularly used to determine the tensile strength of brittle materials due to its simplicity in sample preparation and test conduction. Therefore, it is suggested by the ISRM and ASTM as a recommended method for static tensile strength measurement of rocks. Split-tensile tests are conducted at both quasi-static and dynamic states in this study. A pair of strain gauges are glued to the specimen's centre to measure the compressive strain and the split-tensile strain. The applied compressive force is recorded using the inbuilt load cell in the testing system.

Eighteen split-tensile tests are conducted at quasi-static and low-strain rate states (6 specimens for each type of brick). Table 5-1 summarizes the testing results. It is to note the displacement control method is used for the split-tensile tests at constant loading rates. However, the induced loading rate and strain rate in the specimens are not controllable in this indirect testing method. As shown in Table 5-1, under the loading rates of 1.03×10^{-5} GPa/s and 3.65×10^{-5} GPa/s, there is no obvious increase in the split-tensile strengths. For the Common Solid bricks, an average of 2.48 MPa split-tensile strength is measured at 1.03×10^{-5} GPa/s loading rate, while 2.51 MPa is found at 2.05×10^{-5} GPa/s loading rate. It indicates a negligible strain rate effect under low-speed split-tension. Similar observations can be found for Limestone Hues and Copper Brown bricks, respectively. The DIF is calculated from each strength/strain/modulus divided by the averaged quasi-static strength/strain/modulus for each type of brick.

Table 5-1 Split-tensile test results at quasi-static and low-strain rate state

Brick type	Loading rate GPa/s	Strain rate /s	Tensile strength MPa	Strain mm/mm	Young's modulus GPa	DIF (strength)	DIF (strain)	DIF (E)
Common Solid	1.03E-05	1.33E-06	2.43	5.29E-04	6.4	0.98	0.98	0.88
Common Solid	1.03E-05	1.33E-06	2.32	5.66E-04	7.3	0.94	1.05	1.00
Common Solid	1.03E-05	1.33E-06	2.69	5.28E-04	8.2	1.08	0.98	1.12
Common Solid	2.05E-05	2.65E-06	2.66	4.63E-04	7.6	1.07	0.86	1.03
Common Solid	2.05E-05	2.65E-06	2.51	5.94E-04	7.2	1.01	1.10	0.99
Common Solid	2.05E-05	2.65E-06	2.35	5.77E-04	6.8	0.95	1.07	0.93
Limestone Hue	1.13E-05	1.45E-06	2.06	4.21E-04	7.6	1.05	1.16	1.10
Limestone Hue	1.13E-05	1.45E-06	1.86	3.58E-04	6.2	0.95	0.98	0.90
Limestone Hue	1.13E-05	1.45E-06	1.97	3.14E-04	6.9	1.00	0.86	1.00
Limestone Hue	3.65E-05	4.70E-06	2.04	4.73E-04	7.4	1.04	1.30	1.07
Limestone Hue	3.65E-05	4.70E-06	1.88	4.06E-04	7.1	0.96	1.11	1.03
Limestone Hue	3.65E-05	4.70E-06	2.08	5.49E-04	6.5	1.06	1.51	0.94
Copper Brown	1.33E-05	1.54E-06	2.82	5.96E-04	7.9	0.98	0.97	1.00
Copper Brown	1.33E-05	1.54E-06	2.69	6.07E-04	7.2	0.94	0.99	0.91
Copper Brown	1.33E-05	1.54E-06	3.09	6.37E-04	8.6	1.08	1.04	1.09
Copper Brown	2.66E-05	3.08E-06	2.83	6.67E-04	7.3	0.99	1.09	0.93
Copper Brown	2.66E-05	3.08E-06	3.12	8.16E-04	8.4	1.09	1.33	1.06
Copper Brown	2.66E-05	3.08E-06	2.98	6.75E-04	8.1	1.04	1.10	1.02

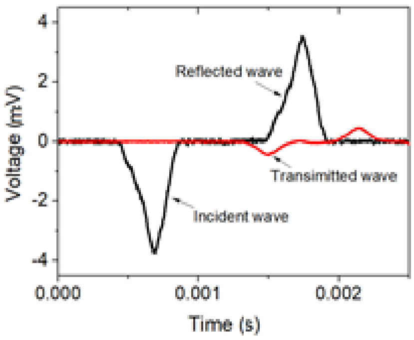
5.1.2 Dynamic split-tensile test

This test was conducted with SHPB system. All discs are designed to be 100 mm diameter and 100 mm length. Firstly, the dynamic split tensile test with proper pulse shaper technique (as mentioned in section 3.2.3 is conducted to check the validation of test result of tensile strength and later proven to achieve the stress equilibriums. A copper pulse shaper is used to help achieve dynamic equilibrium. The copper disc is 3 mm in thickness and 10 mm, 20 mm, or 30 mm in diameter according to different impact speeds used.

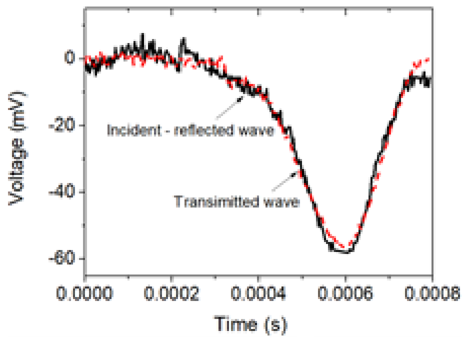
Figure 5-1a shows the typical stress wave signal recorded in the incident and transmitter bars for the split-tensile test. Dynamic equilibrium is checked to ensure the validity of each high-speed split-tensile test (Figure 5-1b). Eq. (14) gives the formula for calculating the split-tensile strength. Strain gauges are also glued to the specimen's centre in the split-tensile direction to monitor specimen strain. Considering the challenge in predicting the actual strain rate that a specimen experienced in a split-tensile test, most researchers utilize loading rate (unit MPa/s from transmitted stress). Some researchers divide the loading rate with Young's modulus of the tested material to derive the strain rate [18]. In this study, both the loading rate from the transmitted stress and strain rate derived by differentiating the recorded strain time histories measured on the specimen are employed.

$$\sigma_t = \frac{2P}{\pi DL} \tag{14}$$

where P is the applied compressive load, D and L are the diameter and length of the specimen.



a)



b)

Figure 5-1 Dynamic split tensile signals: a) typical stress wave signals; and b) dynamic equilibrium of the dynamic split-tensile tests using the SHPB system

A total of 62 dynamic split-tensile tests are conducted with various vessel pressures from 0.1 MPa to 0.3 MPa for launching the striker bar of the SHPB system, which results in loading rates between 21.15 GPa/s to 101.71 GPa/s on the specimens, and the strain rates measured by the strain gauges on the specimen varies between 3.06 /s and 14.14 /s. Table 5-2 summarizes the dynamic split-tensile testing results.

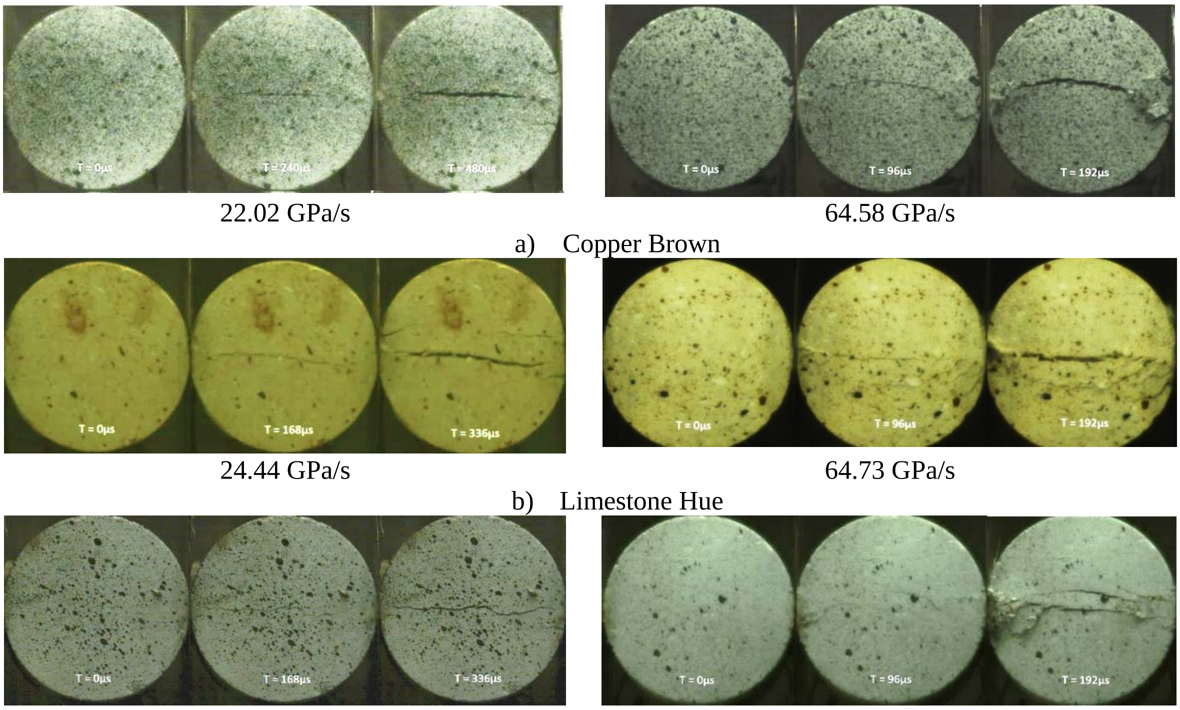
Table 5-2 Dynamic split-tensile test results

Brick type	Loading rate GPa/s	Strain rate /s	Tensile strength MPa	Strain mm/mm	Young's modulus GPa	DIF (strength)	DIF (strain)	DIF (E)
Common Solid	21.15	3.09	4.57	6.43E-04	8.3	1.84	1.19	1.1
Common Solid	26.43	3.87	4.76	7.19E-04	8.1	1.92	1.33	1.1
Common Solid	29.99	4.39	4.35	5.16E-04	8.3	1.75	0.95	1.1
Common Solid	32.06	4.69	5.21	6.55E-04	7.3	2.10	1.21	1.0
Common Solid	36.35	5.32	5.37	7.15E-04	8.1	2.16	1.32	1.1
Common Solid	36.44	5.33	6.56	7.71E-04	8.6	2.65	1.43	1.2
Common Solid	45.69	6.68	5.37	7.92E-04	7.3	2.17	1.46	1.0
Common Solid	46.85	6.85	5.74	7.52E-04	7.4	2.31	1.39	1.0
Common Solid	46.98	6.87	7.05	7.04E-04	9.4	2.84	1.30	1.3
Common Solid	48.61	7.11	6.56	9.88E-04	7.2	2.65	1.83	1.0
Common Solid	48.8	7.14	6.1	9.02E-04	8.3	2.46	1.67	1.1
Common Solid	49.96	7.31	7.37	8.03E-04	7.5	2.97	1.48	1.0
Common Solid	51.29	7.50	5.77	1.05E-03	8.5	2.33	1.94	1.2
Common Solid	53.29	7.80	6.15	9.27E-04	8.2	2.48	1.71	1.1
Common Solid	58.32	8.53	7.09	9.63E-04	9.4	2.86	1.78	1.3

Common Solid	60.37	8.83	7.61	1.26E-03	8.1	3.07	2.33	1.1
Common Solid	67.74	9.91	7.8	1.45E-03	8.6	3.15	2.68	1.2
Common Solid	70.48	10.31	7.61	1.05E-03	10	3.07	1.94	1.4
Common Solid	70.56	10.32	7.06	1.11E-03	8.9	2.85	2.05	1.2
Common Solid	79.54	11.64	7.44	1.42E-03	8.1	3.00	2.62	1.1
Limestone Hue	23.35	3.50	3.63	5.98E-04	7.8	1.8	1.64	1.13
Limestone Hue	20.38	3.06	5.14	7.41E-04	7.16	2.6	2.03	1.04
Limestone Hue	24.44	3.67	4.07	7.43E-04	7.8	2.1	2.04	1.13
Limestone Hue	26.45	3.97	5.79	0.000704	7.7	3.0	1.93	1.12
Limestone Hue	31.43	4.71	3.91	6.41E-04	8	2.0	1.76	1.16
Limestone Hue	34.04	5.11	5.24	7.18E-04	7.6	2.7	1.97	1.10
Limestone Hue	38.72	5.81	5.90	6.67E-04	8.25	3.0	1.83	1.20
Limestone Hue	41.87	6.28	6.18	9.06E-04	8.7	3.1	2.49	1.26
Limestone Hue	45.1	6.77	5.31	9.47E-04	7.7	2.7	2.60	1.12
Limestone Hue	46.23	6.93	6.55	8.74E-04	8.9	3.3	2.40	1.29
Limestone Hue	46.77	7.02	7.02	1.24E-03	9.38	3.6	3.39	1.36
Limestone Hue	50.51	7.58	6.69	1.31E-03	8.3	3.4	3.61	1.20
Limestone Hue	53.72	8.06	6.07	1.16E-03	8.3	3.1	3.18	1.20
Limestone Hue	55.58	8.34	6.19	7.64E-04	9.1	3.2	2.10	1.32
Limestone Hue	58.53	8.78	7.62	9.88E-04	10.2	3.9	2.71	1.48
Limestone Hue	59.06	8.86	6.79	9.01E-04	8.7	3.5	2.47	1.26
Limestone Hue	60.82	9.12	6.08	9.55E-04	9.4	3.1	2.62	1.36
Limestone Hue	61.72	9.26	7.03	1.23E-03	7.7	3.6	3.38	1.12
Limestone Hue	64.73	9.71	6.74	1.13E-03	9.8	3.4	3.10	1.42
Limestone Hue	66.56	9.98	6.99	9.81E-04	10.9	3.6	2.69	1.58
Limestone Hue	67.25	10.09	6.71	1.06E-03	9.1	3.4	2.91	1.32
Copper Brown	22.02	3.06	4.95	6.47E-04	8.1	1.73	1.05	1.03
Copper Brown	36.98	5.14	7.40	1.09E-03	8.5	2.58	1.77	1.08
Copper Brown	40.17	5.59	6.43	6.44E-04	8.7	2.24	1.05	1.10
Copper Brown	41.09	5.71	7.40	8.27E-04	9.2	2.58	1.35	1.16
Copper Brown	45.10	6.27	6.98	8.69E-04	8.6	2.44	1.42	1.09
Copper Brown	45.27	6.29	8.26	9.49E-04	9.4	2.88	1.55	1.19
Copper Brown	49.95	6.95	6.83	7.31E-04	9.1	2.38	1.19	1.15
Copper Brown	52.48	7.30	8.40	1.12E-03	9.2	2.93	1.82	1.16
Copper Brown	56.33	7.83	8.59	9.73E-04	9.5	3.00	1.59	1.20
Copper Brown	56.33	7.83	8.59	1.21E-03	10.5	3.00	1.98	1.32
Copper Brown	58.18	8.09	8.73	1.22E-03	10.8	3.04	1.99	1.36
Copper Brown	58.62	8.15	8.02	1.36E-03	9.5	2.80	2.22	1.20
Copper Brown	59.77	8.31	8.07	9.13E-04	10.7	2.81	1.49	1.36
Copper Brown	64.58	8.98	8.88	1.01E-03	11.3	3.10	1.65	1.43
Copper Brown	64.66	8.99	8.08	1.19E-03	9.5	2.82	1.94	1.19
Copper Brown	70.03	9.74	10.50	1.18E-03	12.0	3.66	1.92	1.52
Copper Brown	76.90	10.69	8.91	9.45E-04	11.4	3.11	1.54	1.44
Copper Brown	85.81	11.93	10.73	1.47E-03	12.0	3.74	2.40	1.51
Copper Brown	91.57	12.73	9.87	1.22E-03	11.7	3.44	1.99	1.48
Copper Brown	95.13	13.23	9.73	1.13E-03	11.9	3.40	1.84	1.51
Copper Brown	101.71	14.14	12.71	1.39E-03	12.2	4.44	2.27	1.54

5.1.3 *Dynamic split-tensile test analysis*

Figure 5-2 shows the dynamic fracturing processes of brick specimens, which are recorded using a high-speed camera with a filming rate of 40 kHz. Prior to the test, the specimens are painted into white colour and sprayed with black dots for digital image correlation analysis. Figure 5-2a shows the fracture processes of the Copper Brown bricks. It is clear that under 22.02 GPa/s loading rate, at t = 240 μs the first crack initiates from the centre of the sample, which then extends towards both ends of the specimen leading to the failure of the specimen at t = 480 μs. Under the increased loading rate (64.58 GPa/s), a crack is formed around the centre of the specimen at an earlier stage (t = 96 μs), with the contacting end crushed at the left end of the cylinder. A thorough split failure is developed at t = 192μs with both ends of the specimen crushed. Similar fracture processes can be observed on the Limestone Hue specimens, as illustrated in Figure 5-2b. More severe end crushing can be observed on the Common Solid brick specimen at a high loading rate (67.74 GPa/s) in which multiple cracks in the centre of the specimen are developed. This is because of the increased stress wave intensity applied through the incident bar onto the specimen.



22.02 GPa/s 64.58 GPa/s

a) Copper Brown

24.44 GPa/s 64.73 GPa/s

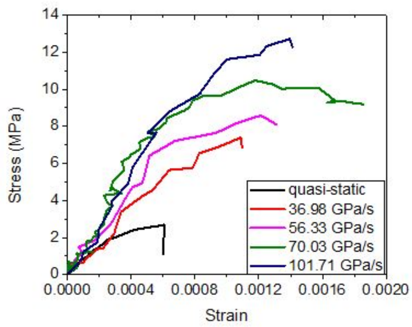
b) Limestone Hue

32.06 GPa/s 67.74 GPa/s

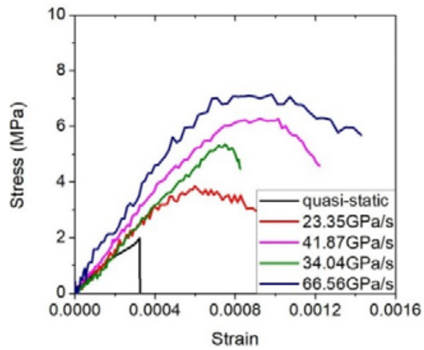
c) Common Solid

Figure 5-2 Fracture processes of the bricks under dynamic split-tension

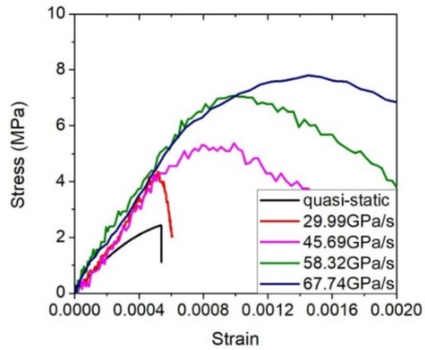
Typical stress-strain curves of the specimens at different loading rates are shown in Figure 5-3. As depicted, all three bricks exhibit strong strain rate sensitivity. A split-tensile strength of 2 MPa is measured for the Limestone Hue at a quasi-static state, which increases apparently as the loading rate increases. The split-tensile strength rises to about 3.6 MPa at 23.35 GPa/s loading rate and further to about 7 MPa at 66.56 GPa/s loading rate. The modulus also appears to increase at increased loading rates. Under a quasi-static state, a modulus of about 7.6 GPa is measured, which increases slightly to about 7.8 GPa at a 23.35 GPa/s loading rate. Under 41.87 GPa/s loading rate, the modulus further increases to about 8.7 GPa. A similar observation can be found on the Common Solid and Copper Brown bricks that both the tensile strength and the modulus measured increase as the loading rate is increased. It is worth noting that the failure strain (corresponding to peak tensile stress) of the Common Solid and Copper Brown bricks are larger than those of the Limestone Hue bricks, indicating the latter is more brittle.



a) Copper Brown



b) Limestone Hue



c) Common Solid

Figure 5-3 Typical stress-strain curves of the bricks from split-tensile tests

5.2 Direct tensile tests

5.2.1 Quasi-static direct tensile test

Eighteen direct tensile tests are carried out. Table 5-3 summarizes the testing results. As the strain rate increases from 2.25×10^{-6} /s to 2.25×10^{-3} /s by 1000 times, the tensile strengths are found to increase by 26.7 %, 18.9 % and 25.3 % for the Common Solid, Limestone Hue and Copper Brown bricks, respectively, indicating strain rate sensitivity under low-speed direct tension. And probably because of the existence of more strain rate insensitive aggregates in the Limestone Hue, it exhibits the least strain rate increment comparing with the Copper Brown and Common Solid bricks.

Table 5-3 Direct tensile test results at quasi-static state

Brick type	Loading rate GPa/s	Strain rate /s	Tensile strength MPa	Strain mm/mm	Young's modulus GPa	DIF (strength)	DIF (strain)	DIF (E)
Common Solid	1.52E-05	2.25E-06	2.30	5.19E-04	7.8	1.03	0.89	1.14
Common Solid	1.52E-05	2.25E-06	2.19	5.72E-04	6.5	0.99	0.98	0.95
Common Solid	1.52E-05	2.25E-06	2.18	6.51E-04	6.2	0.98	1.12	0.91
Common Solid	1.52E-02	2.25E-03	2.69	7.01E-04	7.0	1.21	1.21	1.03
Common Solid	1.52E-02	2.25E-03	2.87	5.19E-04	8.6	1.29	0.89	1.26
Common Solid	1.52E-02	2.25E-03	2.88	6.04E-04	7.8	1.30	1.04	1.15
Limestone Hue	1.48E-05	2.25E-06	1.90	5.24E-04	6.2	1.02	1.13	0.93
Limestone Hue	1.48E-05	2.25E-06	1.85	4.46E-04	7.3	0.99	0.96	1.10
Limestone Hue	1.48E-05	2.25E-06	1.84	4.22E-04	6.5	0.99	0.91	0.98
Limestone Hue	1.48E-02	2.25E-03	2.26	6.05E-04	6.5	1.21	1.31	0.98
Limestone Hue	1.48E-02	2.25E-03	2.21	4.93E-04	7.1	1.19	1.06	1.07
Limestone Hue	1.48E-02	2.25E-03	2.18	3.25E-04	7.9	1.17	0.70	1.19
Copper Brown	1.60E-05	2.25E-06	2.63	6.80E-04	7.0	0.98	1.11	0.97
Copper Brown	1.60E-05	2.25E-06	2.76	5.39E-04	8.1	1.03	0.88	1.12
Copper Brown	1.60E-05	2.25E-06	2.66	6.27E-04	6.5	0.99	1.02	0.90
Copper Brown	1.60E-02	2.25E-03	3.43	6.56E-04	8.7	1.28	1.07	1.21
Copper Brown	1.60E-02	2.25E-03	3.39	6.93E-04	8.3	1.26	1.13	1.15
Copper Brown	1.60E-02	2.25E-03	3.28	7.21E-04	7.1	1.22	1.17	0.99

5.2.2 Dynamic direct tensile test results

A total of 30 dynamic direct tensile tests are conducted, which cover loading rates from 54.6 GPa/s to 187.9 GPa/s that corresponding to a strain rate range between 7.59 /s and 26.13 /s. Table 4-2 summarizes the dynamic direct tensile testing results.

Table 5-4 Dynamic direct tensile testing results

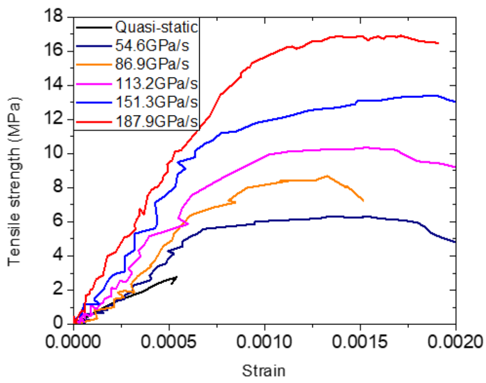
Brick type	Loading rate GPa/s	Strain rate /s	Tensile strength MPa	Strain mm/mm	Young's modulus GPa	DIF (strength)	DIF (strain)	DIF (E)
Common Solid	63.5	9.30	4.85	0.00071	7.5	2.18	1.23	1.10
Common Solid	75.2	11.01	5.30	0.00110	8.1	2.39	1.89	1.18
Common Solid	76.4	11.17	6.18	0.00148	8.2	2.78	2.54	1.20
Common Solid	78.5	11.49	5.50	0.00118	7.4	2.48	2.04	1.08
Common Solid	88.8	13.00	6.32	0.00147	6.9	2.84	2.54	1.00
Common Solid	110.1	16.10	8.57	0.00138	8.1	3.86	2.39	1.19
Common Solid	117.0	17.12	8.97	0.00122	9.5	4.04	2.09	1.39
Common Solid	129.4	18.93	9.70	0.00162	10.1	4.37	2.78	1.47
Common Solid	142.4	20.84	9.97	0.00198	9.1	4.49	3.41	1.33
Common Solid	173.3	25.36	11.00	0.00148	11.1	4.95	2.56	1.62
Limestone Hue	104.1	15.62	7.29	0.00128	8.3	3.91	2.77	1.25
Limestone Hue	116.9	17.53	7.89	0.00149	7.6	4.23	3.22	1.14
Limestone Hue	119.5	17.92	8.96	0.00104	9.2	4.81	2.24	1.38
Limestone Hue	131.2	19.69	9.84	0.00132	9.1	5.28	2.84	1.36
Limestone Hue	148.9	22.34	11.17	0.00130	10.8	6.00	2.80	1.62
Limestone Hue	150.2	22.54	11.27	0.00153	10.1	6.05	3.30	1.52
Limestone Hue	152.7	22.90	11.45	0.00141	11.3	6.15	3.04	1.70

Limestone Hue	157.0	23.55	11.78	0.00178	12.2	6.32	3.83	1.83
Limestone Hue	158.0	23.69	10.50	0.00168	11.0	5.64	3.62	1.66
Limestone Hue	173.4	26.02	13.01	0.00136	14.1	6.98	2.94	2.11
Copper Brown	54.6	7.59	6.31	0.00155	8.9	2.35	2.51	1.24
Copper Brown	80.5	11.20	8.20	0.00125	9.1	3.05	2.04	1.27
Copper Brown	86.9	12.08	8.69	0.00133	10.1	3.24	2.16	1.41
Copper Brown	111.1	15.45	9.33	0.00136	11.0	3.48	2.21	1.53
Copper Brown	113.2	15.74	10.29	0.00146	12.3	3.83	2.38	1.71
Copper Brown	137.4	19.11	12.37	0.00184	15.8	4.61	2.99	2.20
Copper Brown	139.0	19.33	11.30	0.00194	13.1	4.21	3.15	1.82
Copper Brown	143.5	19.95	11.50	0.00161	14.7	4.28	2.61	2.04
Copper Brown	151.3	21.04	13.40	0.00190	16.3	4.99	3.09	2.27
Copper Brown	187.9	26.13	16.91	0.00171	18.7	6.30	2.78	2.60

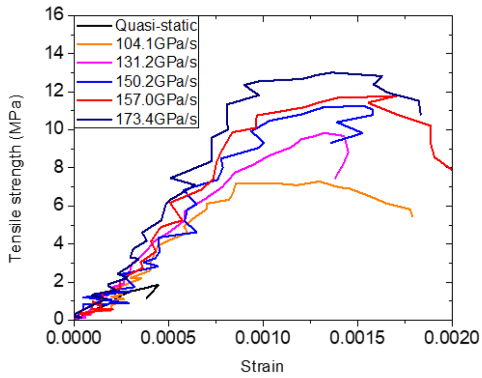
5.2.3 Direct tensile test results analysis

Figure 5-4 show the typical stress-strain curves at different strain rates under direct tension. The average quasi-static direct tensile strengths are 2.68 MPa, 1.86 MPa and 2.22 MPa for the Copper Brown, Limestone Hue and Common Solid bricks, respectively. All three bricks show different levels of dynamic strength increments. For the Copper Brown brick, the dynamic direct tensile strength increases from 2.68 MPa at a quasi-static state to 6.31 MPa at 54.6 GPa/s loading rate, and further to 16.91 MPa at a loading rate of 187.9 GPa/s. A consistent increase of modulus can also be observed, which increases from 7.9 GPa at a quasi-static state to 8.9 GPa at a loading rate of 54.6 GPa/s and to 18.7 GPa at a loading rate of 187.9 GPa/s. Similar increasing trends on dynamic increase effects can be found on the Limestone Hue and Common Solid bricks.

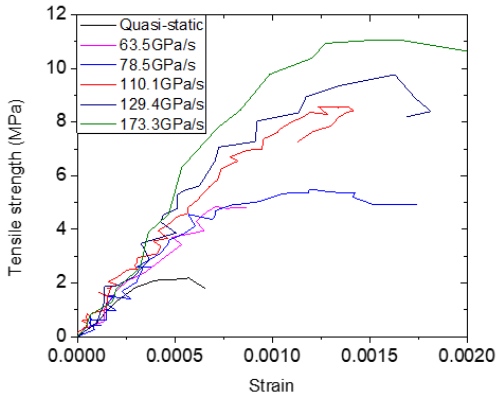
Figure 5-5 show the fracturing images for the three types of bricks. Under dynamic direct tension, brick specimens fracture from different locations but still primarily around specimen centres which are therefore not influenced by the fixing ends. It demonstrates the validity of the dynamic direct tensile tests, and the influence of boundary condition is negligible. Comparing with the dynamic split-tensile test, which is prone to contact surface crushing, the dynamic direct tensile test is more ideal to ensure test validity.



a) Copper Brown

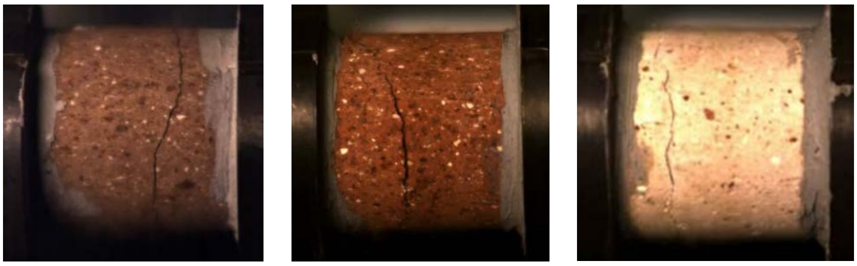


b) Limestone Hue



c) Common Solid

Figure 5-4 Typical stress-strain curves of the bricks from direct tensile tests



a) Copper Brown (80.5 GPa/s) b) Common Solid (63.5 GPa/s) c) Limestone Hue (104.1 GPa/s)

Figure 5-5 Typical fracture images for the bricks under dynamic direct tension

5.3 Correlation between split-tensile and direct tensile properties

The above laboratory testing data on the tensile properties of the three types of bricks are analyzed in this section. Correlation between the split-tensile properties and direct tensile properties, including tensile strength and modulus, are derived for the dynamic testing condition. Dynamic increase effect on tensile strength and modulus for the bricks are analyzed by comparing with existing testing data on brick and similar materials. The empirical formula of DIF for tensile strength is generated by modifying the popularly used CEB (Comité Euro-International du Béton) model.

Figure 5-6 summarizes the dynamic tensile strengths measured from both the split-tensile tests and the direct tensile tests at different loading rates. The dynamic split-tensile test covers loading rates from 21.15 GPa/s to 101.71 GPa/s (corresponding to strain rate range of 3.06 /s to 14.14 /s), while the dynamic direct tensile test covers a higher range between 54.6 GPa/s and 187.9 GPa/s (corresponding to strain rate range of 7.59 /s to 26.02 /s). It can be observed that the dynamic split-tensile strength is higher than the dynamic direct tensile strength at the overlapping loading rate of 60 GPa/s to 100 GPa/s, which are consistent for all three types of bricks. Also, the direct tensile strengths are found more consistent than split-tensile strengths. This is because, under dynamic split-tension, the formation of multiple cracks and edge failure due to stress concentration and high amplitude incident stress wave could lead to higher stress transmitted and measured, while in the direct tensile tests, only a single failure crack is formed. Moreover, the previous study by Hao et al. [51] observed the lateral confinement effect in dynamic direct tensile tests. Since more inertia confinement is involved in the dynamic split-tensile test, the more significant lateral inertial force could be induced. Nevertheless, there is no study yet to quantify the influence of lateral inertial confinement for dynamic split-tensile tests, which can be quantified and compared in future studies. Also, in the direct tensile test, the crack tends to be developed from the relatively weaker section. Despite under dynamic loading condition, the stress wave will propagate through the specimen leaving much less time for cracks to be initiated from the weak section. In comparison, in a dynamic split-tensile test, fracture occurs across the centre line of the cylindrical specimen regardless of the strong aggregates or weak sections.

In order to correlate the dynamic tensile strengths measured from split-tensile tests and direct tensile test, the following empirical formula is proposed based on the testing data:

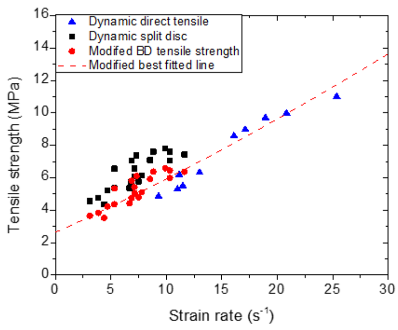
$$\sigma_{DT} = \sigma_{BD} \times Log\,(\frac{\dot{\varepsilon}}{10} + 6) \tag{15}$$

where σ_{DT} is the dynamic direct tensile strength, and σ_{BD} is the dynamic split-tension strength, and LR is the loading rate. As shown in Figure 5-6, after correlation using the above formula, the modified split-tensile strengths fit well with the direct tensile strengths. This formula can therefore be employed to estimate the dynamic direct tensile strength of bricks using the dynamic split-tensile strength measured from more convenient, dynamic split-tensile tests.

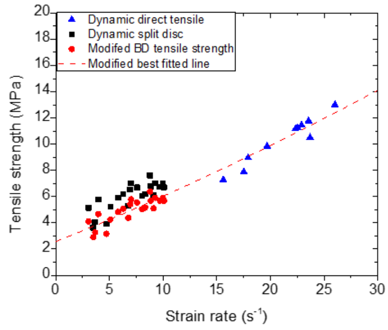
Figure 5-7 shows the failure strains (corresponding to the tensile strength) measured for both the split-tensile tests and the direct tensile tests. It can be found the data correlate well, which increases gradually with the increase of loading rates. No modification is needed since these strains are measured directly on specimens using strain gauges. Being similar to the relation on tensile strength, Figure 5-7 show Young's modulus derived from the split-tensile tests and the direct tensile tests. Slight increments can be found on the modulus as the loading rate increase on both split tension and direct tensile tests. Similarly, an empirical formula can be derived as Eq. (16) below to correlate the dynamic modulus from the direct tensile test and split-tensile test.

$$E_{DT} = E_{BD} \times Log\,(\frac{\dot{\varepsilon}}{10} + 6) \qquad (16)$$

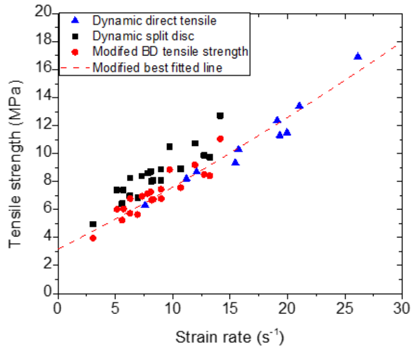
where E_{DT} is Young's modulus from the dynamic direct tensile test, E_{BD} is Young's modulus derived from the dynamic split-tensile test, and LR is the loading rate. It can be seen from Figure 5-8 that after modification using Eq. (16), Young's modulus could agree well for all three types of bricks.



a) Common Solid

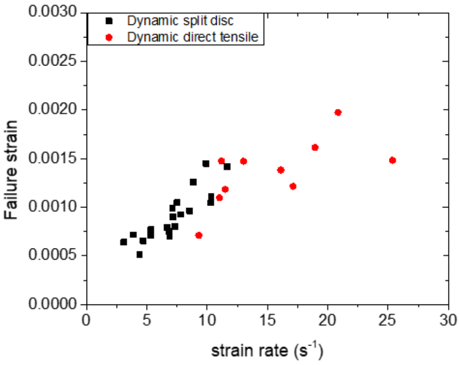


b) Limestone Hue

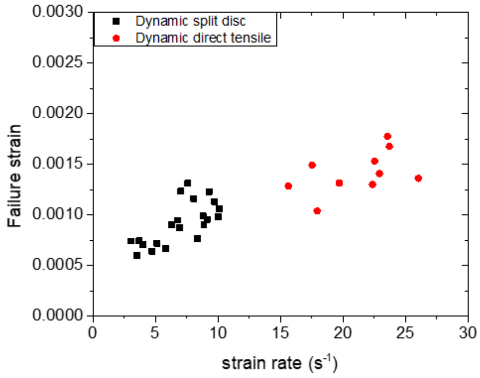


c) Copper Brown

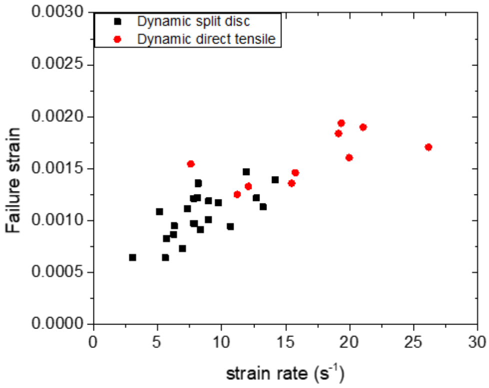
Figure 5-6 Tensile strengths at different loading rates



a) Common Solid

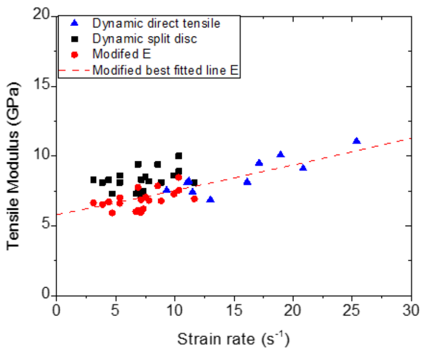


b) Limestone Hue

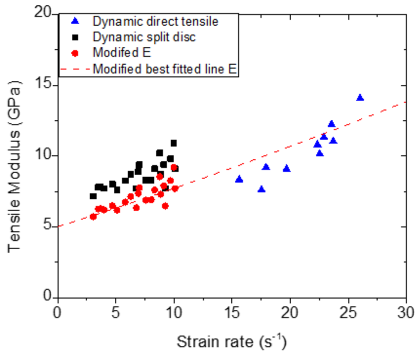


c) Copper Brown

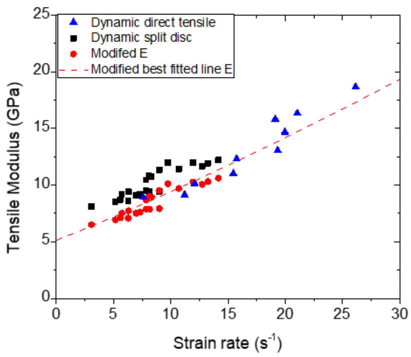
Figure 5-7 Tensile strains at different loading rates



a) Common Solid



b) Limestone Hue



c) Copper Brown

Figure 5-8 Young's modulus at different loading rates

5.4 Dynamic increase effect and comparison with past research

Dynamic increase factor (DIF), i.e. dynamic strength over quasi-static strength, is commonly used in analysis and design. DIF for the tensile strengths of the three types of bricks from both split-tensile tests and direct tensile tests are summarized and plotted versus strain rates in Figure 5-9. Existing data for clay bricks in the open literature is included for comparison. Since there is a lack of testing data on brick material, considering the similarity in composition and mechanical properties, some popularly used dynamic tensile strength data on mortar [67, 68] and concrete [68-70] are also included in the comparison. Larcher et al. [41] reported tensile DIF of about 2.2 and 3.0 for Clinker and Terracotta bricks, indicating a substantial dynamic increase effect. However, the strain rate was about 100/s through the split-tensile testing method using a SHPB system, which is questionable since it is much higher than the commonly achievable strain rate range by such a system and testing method. The tensile DIFs for mortar by Chen et al. [67] and Ross and Tedesco [68] show similar increasing trends with the split-tensile testing data on bricks between strain rate 5 /s and 15 /s, which indicates the tensile DIF for the low compressive strength material can demonstrate a similar but not identical behaviour. The DIFs for concrete by Ross and his co-works [68-70] scatter between 1.0 to 4.0 at strain rate 1 /s to 12 /s. The variation may due to specimen size [71] and testing methods not only limited to the static strength. Ross and Tedesco [68] show the DIF of tensile strength falls between 2.7 to 3.7 for the split tensile tests and falls 1.6 to 2.7 for direct tensile tests at similar strain rates on the same type of concrete.

Figure 5-10 shows the DIF data for the tensile strength of the three types of clay bricks covering strain rates between 10^{-6} /s and about 30 /s. Empirical trendlines by other researchers for concrete are also included for comparison. When compared with the DIF relation recommended by CEB [72] for 30 MPa concrete, an apparent difference can be observed, which substantially underestimates the DIF for bricks. Based on the CEB model, Ross et al. proposed a modified DIF relation for concrete, which appears to align much better with the DIF data for bricks in this study. With a more dynamic test on concrete available, Malvar and Crawford [71] provided their DIF relation for low-strength concrete, in which the strain rate for the transition point is lower, and DIFs are slightly higher. These differences are mainly attributed to the different composite (no large aggregates in clay bricks) and the different mechanical properties between bricks and low-strength concrete. For example, the strength of clay bricks is much lower than concrete (even comparing to low-strength concrete), and the porosity of brick is smaller than concrete, etc. Therefore, to more accurately model brick dynamic properties, it is necessary to derive a more suitable DIF formula.

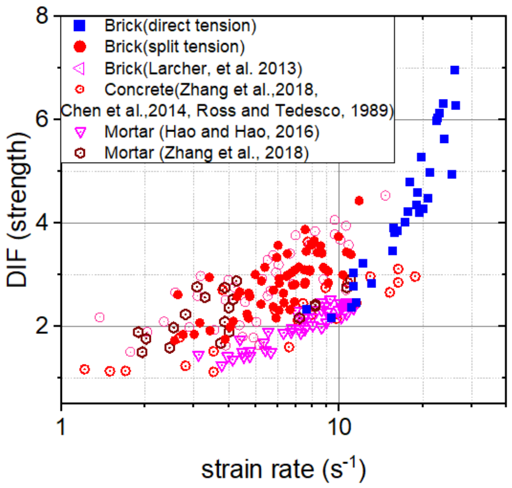


Figure 5-9 Strength vs. loading rate

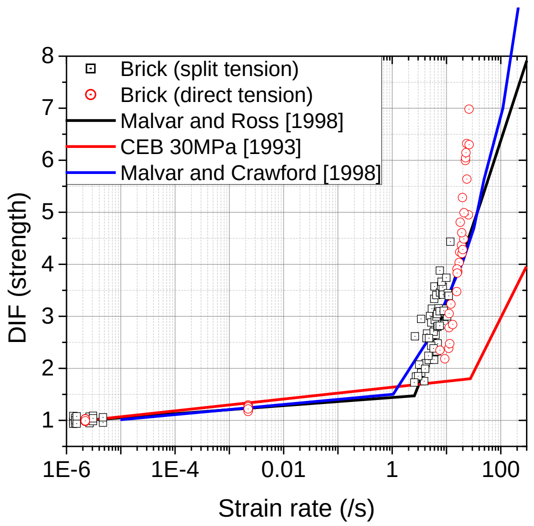


Figure 5-10 Comparison of existing DIF trendlines with brick testing data

5.5 Proposed tensile DIF formulae for bricks

In order to derive the DIF relation for clay bricks, the DIF formulae are based on the CEB model for easy application, and some modifications are made for accurate prediction. CEB (Euro-

International Committee for Concrete) provides DIF relations for concrete under both compression and tension, which is widely used by researchers and engineers. CEB-FIP Model Code 1990, which is the original CEB model, is found properly fit concrete compression and tension DIF by employing the transition point at 30 /s. Later, the model has been used and modified by researchers to improve the fitting. Malver and Crawford in 1998 has found the transition point fall at 1 /s and modified the bilinear formulas for fitting of the test data. CEB model has also been used and modified for UHPC (ultra-high performance concrete). Nevertheless, it is constantly criticized to underestimate the tensile DIF of concrete when compared with testing data [71, 73, 74]. Based on more laboratory testing results on concrete, Ross and his colleagues [70, 75] modified the DIF relation by CEB for better accuracy.

A bi-linear relation is employed. Based on testing data, the strain rate for the transition point is 5/s. Since a strong dynamic increase effect is found where the slope for the DIF-strain rate relation is steep as in Figure 15, a linear regression magnitude of 0.8 is used instead of 1/3 for concrete. The CEB model utilizes the compressive strength to normalize a reference concrete strength of 10 MPa to take account of the difference in DIF for concrete with different strengths. However, when considering tensile properties, this may not be appropriate, especially for brick. The compressive strength over direct tensile strength ratio is about 10 for concrete ($f_c/f_t = 10$). But this ratio varies for bricks. For example, in Larcher et al.'s study [41] the ratio of f_c/f_t is 16.4 for Clinker and 5.1 for Adobe brick. For the clay bricks in this study, Limestone Hue brick exhibits a higher f_c/f_t rato of 10.95 (direct tension), and for Common solid brick, the f_c/f_t ratio are 8.33. This can be explained by the different material compositions, such as the size of the clay mixtures and aggregates and the percentage of the silica, which show different sensitivity to the strain rate effect. Higher compressive strength is found on the brick with a higher silica ratio. However, the tensile strength is not proportional to the silica content and compressive strength. For example, the mid-strength (compression) Limestone Hue brick has the lowest tensile strength because of the different clay mixtures and smaller sizes of aggregates that leads to weak bonding. In the modified DIF formulae, the ratio of f_c/f_t is employed to consider both brick compressive strength and tensile strength influences.

$$DIF_t = \frac{f_{d,t}}{f_{s,t}} = \begin{cases} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} & when\ \dot{\varepsilon} \leq 5\ s^{-1} \\ \beta\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{0.85} & when\ \dot{\varepsilon} > 5\ s^{-1} \end{cases} \tag{17}$$

where $f_{d,t}$ and $f_{s,t}$ are the dynamic and quasi-static tensile strength. $\beta = 10^{7\delta-5.7}$, and $\delta = \frac{2.5(\frac{f_{s,c}}{f_{s,t}})}{1000}$ in which $f_{s,c}$ is the quasi-static compressive strength. $\dot{\varepsilon}_s = 1.0\times10^{-6}$ /s for direct tensile strength. And the split tensile strengths for different bricks have been modified into direct tensile strength using Eq. (15). The static compressive strengths are 24.8 MPa, 18.5 MPa and 20.4 MPa for Copper Brown, Limestone Hue and Common Solid bricks, respectively, as in chapter 4 the brick compressive strength. δ can be calculated for different bricks, and the DIF relation can be determined. Figure 5-11 show the proposed tensile strength DIF fitted line and the experimental data, from which good agreement can be found.

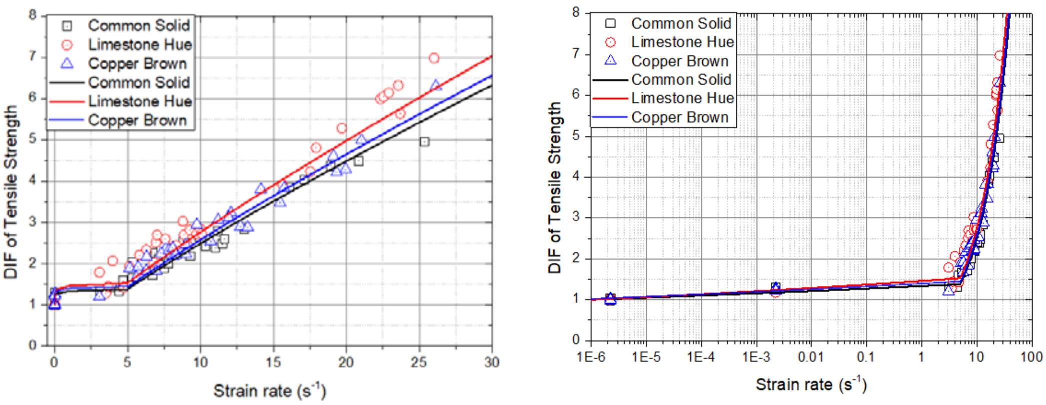


Figure 5-11 The proposed DIF relations for bricks

Chapter 6 Conclusions and Recommended Future Work

6.1 Conclusions

This study investigates the dynamic material properties of clay bricks. Three types of clay bricks made with Western Australian clays are studied. Firstly, the compressive properties of these clay bricks are examined. Both low-speed and high-speed uniaxial compressive tests are performed, covering the strain rate range from 1.67×10^{-5}/s to 0.08/s and 190/s to 340/s. The test results reveal strain rate effect on the compressive strength, ultimate strain and Young's modulus. As loading speed increases, more fractured brick pieces and finer fragments are collected after the tests. It can be explained that higher impact energy is absorbed by the specimen and resulted in more numbers of finer fragments during the high strain rate test. Empirical formulae of DIFs for compressive strength, ultimate strain and Young's modulus with the strain rate for the three types of bricks are derived and presented, which can later be used to model masonry structure under dynamic loads. Comparisons with other researcher's dynamic tests on bricks found different DIF relations with strain rates, indicating the DIF sensitivity is dependent on the material composition and contents of brick material.

In the second part of this study, the tensile properties of clay bricks are studied in depth. Both direct tensile test and indirect split-tensile test are carried out to determine the tensile strength, corresponding failure strain, and Young's modulus of three types of clay bricks at both quasi-static and dynamic states covering strain rates between 1×10^{-6} /s to about 25 /s. The dynamic split-tensile test and direct tensile test are performed using a SHPB and a SHTB system. Different clamping methods are performed to improve the efficiency of dynamic direct tensile test and compared. A screw-on clamp is developed and validated, which can provide similar testing performance as the directly glue-on method. Testing results demonstrate both brick tensile strength and Young's modulus are sensitive to strain rate effect, especially at high strain rate. The relationship between dynamic tensile strength and Young's modulus out of the split-tensile test and direct tensile test are examined. And a correlation formula is proposed, which can be used to estimate the direct tensile properties based on split-tensile properties quickly. The empirical formula of DIF for brick tensile strength at different strain rate is generated using the testing data obtained in this study. The formula is modified from CEB formulae for concrete.

6.2 Recommended future work

This research studies the dynamic material properties of brick materials. Both the dynamic compressive properties and tensile properties are quantified. Based on this study, the following recommendations are given for future work:

1) As reviewed in Chapter 2, there are structural effects such as lateral confinement, axial inertia effect and friction effect, which all influence the dynamic material properties. Future work is recommended to be carried out to quantify and deduct their influences and derive the true dynamic material properties of clay brick.

2) Clay brick is comprised of different mixtures. The micro-structures inside of brick materials could influence the dynamic material properties. Other technologies such as scanning electron microscope (SEM) and nano-indentation method could be employed in the future to investigate the influence of these micro-structure and help to better explain the different dynamic material properties concluded on different brick materials.

3) Despite a decent amount of quasi-static and dynamic tests that have been conducted in this research to derive the empirical formula of DIF. More testing data are still encouraged to enlarge the data pool towards less-biased and more reliable dynamic properties for brick materials.

4) Specimen moisture content could possibly influence the dynamic material properties. Some trial tests in the research were carried out by comparing the dynamic compressive strengths of the oven-dried brick specimen and freshly core-drill/grounded specimens. Different stress signals were found on the transmitter bar of the SHPB system. Therefore, future work could be extended to study the influence of moisture content on dynamic material properties.

Reference

1. Wu, X., et al., *An experimental method to measure dynamic stress–strain relationship of materials at high strain rates.* International Journal of Impact Engineering, 2014. **69**: p. 149-156.
2. Xia, K. and W. Yao, *Dynamic rock tests using split Hopkinson (Kolsky) bar system–A review.* Journal of Rock Mechanics and Geotechnical Engineering, 2015. **7**(1): p. 27-59.
3. Wei, X. and M.G. Stewart, *Model validation and parametric study on the blast response of unreinforced brick masonry walls.* International Journal of Impact Engineering, 2010. **37**(11): p. 1150-1159.
4. Abou-Zeid, B.M., et al., *Response of arching unreinforced concrete masonry walls to blast loading.* Journal of Structural Engineering, 2010. **137**(10): p. 1205-1214.
5. Zhang, X., et al., *Laboratory test on dynamic material properties of annealed float glass.* International Journal of Protective Structures, 2012. **3**(4): p. 407-430.
6. Kim, D., et al., *Numerical simulation of the split hopkinson pressure bar test technique for concrete under compression.* International Journal of Impact Engineering, 2010. **37**(2): p. 141-149.
7. Hao, Y., H. Hao, and X. Zhang, *Numerical analysis of concrete material properties at high strain rate under direct tension.* International Journal of Impact Engineering, 2012. **39**(1): p. 51-62.
8. Zhang, X., et al., *Static and dynamic material properties of CFRP/epoxy laminates.* Construction and Building Materials, 2016. **114**(Supplement C): p. 638-649.
9. Zhang, X., et al., *The mechanical properties of Polyvinyl Butyral (PVB) at high strain rates.* Construction and Building Materials, 2015. **93**(Supplement C): p. 404-415.
10. Zhou, X. and H. Hao, *Modelling of compressive behaviour of concrete-like materials at high strain rate.* International Journal of Solids and Structures, 2008. **45**(17): p. 4648-4661.
11. Defense, U.D.o., *Structures to resist the effects of accidental explosions.*, in *UFC 3-340-02*. 2008, Unified Facilities Criteria: Washington DC.
12. Lindholm, U., *Review of dynamic testing techniques and material behavior*, in *Mechanical properties at high rates of strain*. 1974.
13. Nemat-Nasser, S., *Introduction to high strain rate testing*, ed. m.t.a.e. ASM handbook. 2000, Materials Park OH: ASM International.
14. Ramesh, K.T., *High rates and impact experiments*, in *Springer handbook of experimental solid mechanics*. 2008, Springer. p. 929-960.
15. Sharpe Jr, W.N. and W.N. Sharpe, *Springer handbook of experimental solid mechanics*. 2008: Springer.
16. Lindholm, U., *High strain rate tests, techniques of metals research, measurement of mechanical properties*. 1971, Wiley Interscience, New York.
17. Aassved Hansen, E., *Determination of the Tensile Strength of Concrete.* NORDIC Concrete Research Publicatoins, 1995. **17**: p. 1-17.
18. Zhou, Z., G. Ma, and X. Li. *Dynamic Brazilian splitting and spalling tests for granite*. in *11th ISRM Congress*. 2007. International Society for Rock Mechanics and Rock Engineering.
19. Malcolm Mellor, I.H., *Measurement of Tensile Strength by Diametral Compression of Discs and Annuli.* Engineering Geology, 1971. **5**: p. 173-225.
20. Wu, S., X. Chen, and J. Zhou, *Tensile strength of concrete under static and intermediate strain rates: Correlated results from different testing methods.* Nuclear Engineering and Design, 2012. **250**: p. 173-183.
21. Lu, Y.B. and Q.M. Li, *About the dynamic uniaxial tensile strength of concrete-like materials.* International Journal of Impact Engineering, 2011. **38**(4): p. 171-180.
22. Wright, P., *Comments on an indirect tensile test on concrete cylinders.* Magazine of Concrete Research, 1955. **7**(20): p. 87-96.
23. Johnston, C., *Testing concrete in tension and in compression.* Magazine of Concrete Research, 1968. **20**(65): p. 221-228.

24. Hannant, D., K. Buckley, and J. Croft, *The effect of aggregate size on the use of the cylinder splitting test as a measure of tensile strength.* Matériaux et Construction, 1973. **6**(1): p. 15-21.
25. Komloš, K., *Comments on the long-term tensile strength of plain concrete.* Magazine of concrete Research, 1970. **22**(73): p. 232-238.
26. Kasai, Y., K. Vokoyama, and I. Matsui. *Tensile properties of early-age concrete*. in *Proceedings of Conference on Mechanical Behaviour of Materials.* 1972.
27. Yan, D. and G. Lin, *Dynamic properties of concrete in direct tension.* Cement and Concrete Research, 2006. **36**(7): p. 1371-1378.
28. Perras, M.A. and M.S. Diederichs, *A Review of the Tensile Strength of Rock: Concepts and Testing.* Geotechnical and Geological Engineering, 2014. **32**(2): p. 525-546.
29. Ramesh, C. and S. Chopra, *Determination of tensile strength of concrete and mortar by the split test.* The Indian Concrete Journal, 2012.
30. Ali, I., Lingam, A.B., and Ramchander, K., *A method of determining tensile strength of cement mortar.* Indian concrete journal, 1956: p. 106-123.
31. Popovics, S., *Relations between various strengths of concrete.* Highway Research Record, 1967(210).
32. Pincus, G. and H. Gesund, *EVALUATING TENSILE STRENGTH OF CONCRETE.* Materials Research and Standards, 1965. **5**(9): p. 454-&.
33. Bonzel, J., *Über die Spaltzugfestigkeit des Betons. beton 14.* H, 1964. **3**: p. 108-114.
34. Oluokun, F., *Prediction of concrete tensile strength from its compressive strength: an evaluation of existing relations for normal weight concrete.* Materials Journal, 1991. **88**(3): p. 302-309.
35. Pearson, A. and B. Shackel. *Australian national standards for segmental and flag pavements.* in *7o International Conference on Concrete Block Paving. Sun City, South Africa*. 2003.
36. Singh, S.B. and P. Munjal, *Bond strength and compressive stress-strain characteristics of brick masonry.* Journal of Building Engineering, 2017. **9**: p. 10-16.
37. Poon, C.S. and D. Chan, *Paving blocks made with recycled concrete aggregate and crushed clay brick.* Construction and building materials, 2006. **20**(8): p. 569-577.
38. Lourenço, P.B., J. Almeida, and J.A. Barros, *Experimental investigation of bricks under uniaxial tensile testing.* 2005.
39. Zhang, X., et al., *Free water effect on the dynamic compressive properties of mortar.* Cement and Concrete Composites, 2021. **118**: p. 103933.
40. Zhang, X., et al., *Dynamic compressive properties of Kalgoorlie basalt rock.* International Journal of Rock Mechanics and Mining Sciences, 2020. **135**: p. 104512.
41. Larcher, M., et al., *Dynamic Increase Factor of Masonry Materials: Experimental Investigations*. 2013, ISIEMS-ICPS, Potsdam, Germany.
42. Hao, H. and B. Tarasov, *Experimental study of dynamic material properties of clay brick and mortar at different strain rates.* Australian Journal of Structural Engineering, 2008. **8**(2): p. 117-132.
43. Pereira, J.M., A. Dias, and P.B. Lourenço, *Dynamic properties of clay brick at different strain rates*, in *in: Proceedings of Proc. 12th Canadian Masonry Symposium*. 2013: British Columbia.
44. Field, J.E., et al., *Review of experimental techniques for high rate deformation and shock studies.* 2004. **30**(7): p. 725-775.
45. Davies, E., S.J.J.o.t.M. Hunter, and P.o. Solids, *The dynamic compression testing of solids by the method of the split Hopkinson pressure bar.* 1963. **11**(3): p. 155-179.
46. Li, Q.M. and H. Meng, *About the dynamic strength enhancement of concrete-like materials in a split Hopkinson pressure bar test.* International Journal of Solids and Structures, 2003. **40**(2): p. 343-360.
47. Hao, Y. and H. Hao, *Numerical Investigation of the Dynamic Compressive Behaviour of Rock Materials at High Strain Rate.* Rock Mechanics and Rock Engineering, 2013. **46**(2): p. 373-388.
48. HAKALEHTO, K., *The behaviour of rock under impulse loads: A study using the split Hopkinson bar method.* . Chemistry including Metallurgy Series, 1969.

49. Zhang, M., et al., *Further investigation on the dynamic compressive strength enhancement of concrete-like materials based on split Hopkinson pressure bar tests. Part I: Experiments.* International journal of impact engineering, 2009. **36**(12): p. 1327-1334.
50. Gray III, G. and W.R. Blumenthal, *Split-Hopkinson pressure bar testing of soft materials.* ASM handbook, 2000. **8**: p. 488-496.
51. Hao, Y., H. Hao, and Z. Li, *Influence of end friction confinement on impact tests of concrete material at high strain rate.* International Journal of Impact Engineering, 2013. **60**: p. 82-106.
52. Zhang, X. and H. Hao, *The response of glass window systems to blast loadings: An overview.* International Journal of Protective Structures, 2016. **7**(1): p. 123-154.
53. Rossi, P., *A physical phenomenon which can explain the mechanical behaviour of concrete under high strain rates.* Materials and Structures, 1991. **24**(6): p. 422-424.
54. Rossi, P., *Influence of cracking in the presence of free water on the mechanical behaviour of concrete.* Magazine of concrete research, 1991. **43**(154): p. 53-57.
55. Cui, J., H. Hao, and Y. Shi, *Discussion on the suitability of concrete constitutive models for high-rate response predictions of RC structures.* International Journal of Impact Engineering, 2017. **106**: p. 202-216.
56. Cui, J., et al., *Volumetric properties of concrete under true tri-axial dynamic compressive loadings.* manuscript under review with Cement and Concrete Composites, 2018.
57. Changizi, F. and A. Haddad, *Strength properties of soft clay treated with mixture of nano-SiO2 and recycled polyester fiber.* Journal of Rock Mechanics and Geotechnical Engineering, 2015. **7**(4): p. 367-378.
58. ASTM, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, in *ASTM C39*. 2017, American Socity for Testing and Materials.
59. Guo, R., et al., *Direct dynamic tensile study of concrete materials based on mesoscale model.* International Journal of Impact Engineering, 2020. **143**: p. 103598.
60. Frew, D., M.J. Forrestal, and W. Chen, *Pulse shaping techniques for testing brittle materials with a split Hopkinson pressure bar.* Experimental mechanics, 2002. **42**(1): p. 93-106.
61. Naghdabadi, R., M. Ashrafi, and J. Arghavani, *Experimental and numerical investigation of pulse-shaped split Hopkinson pressure bar test.* Materials Science and Engineering: A, 2012. **539**: p. 285-293.
62. Li, X., et al., *Oscillation elimination in the Hopkinson bar apparatus and resultant complete dynamic stress–strain curves for rocks.* International Journal of Rock Mechanics and Mining Sciences, 2000. **37**(7): p. 1055-1060.
63. Cadoni, E., *Dynamic Characterization of Orthogneiss Rock Subjected to Intermediate and High Strain Rates in Tension.* Rock Mechanics and Rock Engineering, 2010. **43**(6): p. 667-676.
64. Chen, X., S. Wu, and J. Zhou, *Experimental and modeling study of dynamic mechanical properties of cement paste, mortar and concrete.* Construction and Building Materials, 2013. **47**: p. 419-430.
65. CEB, *Concrete Structures under Impact and Impulsive Loading.* Synthesis Report No. 187, Comité européen du béton, 1988.
66. Bischoff, P.H. and S.H. Perry, *Compressive behaviour of concrete at high strain rates.* Materials and Structures, 1991. **24**(6): p. 425-450.
67. Chen, X., S. Wu, and J. Zhou, *Experimental study on dynamic tensile strength of cement mortar using split Hopkinson pressure bar technique.* Journal of Materials in Civil Engineering, 2014. **26**(6): p. 04014005.
68. Ross, C.A. and J. Tedesco, *Split-Hopkinson pressure-bar tests on concrete and mortar in tension and compression.* Materials Journal, 1989. **86**(5): p. 475-481.
69. Ross, C.A., J.W. Tedesco, and S.T. Kuennen, *Effects of strain rate on concrete strength.* Materials Journal, 1995. **92**(1): p. 37-47.
70. Ross, C.A., et al., *Moisture and strain rate effects on concrete strength.* Materials Journal, 1996. **93**(3): p. 293-300.
71. Malvar, L.J. and J.E. Crawford, *Dynamic increase factors for concrete*. 1998, Naval Facilities Engineering Service Center Port hueneme CA.

72. CEB, *CEB-FIP model code 1990: Design code, Comité Euro-International du Béton*. 1993, Thomas Telford Publishing.
73. Thomas, R.J. and A.D. Sorensen, *Review of strain rate effects for UHPC in tension.* Construction and Building Materials, 2017. **153**: p. 846-856.
74. Min, F., Z. Yao, and T. Jiang, *Experimental and numerical study on tensile strength of concrete under different strain rates.* Scientific World Journal, 2014. **2014**: p. 173531.
75. Malvar, L.J. and C.A. Ross, *Review of strain rate effects for concrete in tension.* ACI Materials Journal, 1998. **95**: p. 735-739.

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Position: Associate Professor, Central South University

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Name: Jian Cui

Position: Lecturer, Tianjin University

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