Dynamic Tensile Properties of Clay Brick at High Strain Rates

Y. W. Chiu, X. H. Zhang, H. Hao, and N. Salter

Abstract Clay brick is widely used as construction material of masonry structures in Australia. Structures in cyclone prone regions in Australia are constantly under threats from windborne debris impacts. It is commonly known that materials behave differently under dynamic loading than that under quasi-static state. There is still a lack of dynamic material properties on clay bricks. This paper presents quasi-static and dynamic testing results on two types of WA clay bricks - Limestone Hues and St Common Solid. Brazilian disc tests are conducted to derive the split-tensile properties. Brick strength, strain, Young's modulus at strain rates between 1.13×10^{-5}/s to about 10/s are determined. The DIF (dynamic increase factor) for the two bricks are derived for easy and accurate engineering analysis and numerical modelling of clay brick response under dynamic loading. The results are compared with existing data on brick, mortar and concrete.

Keywords Clay brick · DIF · Dynamic properties · Inertia effect

1 Introduction

It is commonly known that material behaves differently under static and dynamic loading conditions. To accurately analyze and predict structural responses under dynamic loads such as impact and blast loading, much efforts have been paid to investigate the dynamic material properties of various construction materials including concrete, steel, rock, glass, polymers etc. [3, 4, 12, 14–16]. Nevertheless, brick as one of the most widely used materials have been less studied. This is primarily because normal clay brick structures have low blast and impact resistant

---

Y. W. Chiu · X. H. Zhang (✉) · H. Hao
Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia
e-mail: Xihong.zhang@curtin.edu.au

N. Salter
Midland Brick, Middle Swan, WA, Australia

C. M. Wang et al. (eds.), *EASEC16*, Lecture Notes in Civil Engineering 101,
https://doi.org/10.1007/978-981-15-8079-6_64

capacity and therefore less focus has been made on brick dynamic material properties. Also, the different brick materials used in different regions and areas for constructions exhibit different mechanical properties due to different chemical compositions. 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, but also lead to more accurate 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 adopt static material properties for bricks or dynamic material properties at particular strain rates only [5], which do not necessarily lead to accurate predictions of structural responses. Some dynamic test data have been released in literatures on the dynamic material properties of clay bricks. However, the reported data on the dynamic increase effect differ substantially. Dynamic increase factor (DIF) of brick compressive strength are generally from 1.2 to 2.5. Larcher et al. [5] carried out SHPB test on bricks and found DIF of 1.38 at strain rate 189 s^{-1}. Pereira et al. [7] quantified clay brick compressive strength at quasi-static state and 176 s^{-1}. Hao and Tarasov [2] tested the unconfined compressive strength of clay bricks at strain rates between 2.1×10^{-6} s^{-1} and 200 s^{-1} with a triaxial static-dynamic testing machine. Recently, the authors conducted both quasi-static and SHPB dynamic tests on three types of WA clay bricks at strain rate up to 337 s^{-1}, and combined previous testing data by different researchers to derive an empirical formula for clay brick compressive DIF [13]. Till now, very limited data are available on the dynamic tensile properties of clay bricks. In a recent paper [5] three different types of bricks, i.e. terracotta, clinker and abode bricks were examined under quasi-static and dynamic states using Brazilian disk method. A DIF for tensile strength of up to 3.0 was found. There is still a serious short of data on the dynamic tensile properties of brick to derive a reliable DIF versus strain rate relation for proper analysis and design practise.

The aim of this study is to experimentally investigate the dynamic tensile properties of clay bricks used in Western Australia. Two different types of clay bricks (Limestone Hues solid and St Common Solid) were tested. The tests covered strain rate from 1.13×10^{-5} s^{-1} to 10 s^{-1}. The split-tensile strength, corresponding failure strain and modulus at different strain rates were measured. Brick specimen dynamic failure process was monitored. DIF for tensile strength were derived and compared with existing data.

2 Experimental Setup

Two types of clay bricks were provided by major local brick supplier Midland Bricks with mixtures of Western Australian local clays. Table 1 lists the chemical compositions of the two bricks. 74 mm diameter by 37 mm cylindrical specimens were core-drilled from 230 mm × 110 mm × 76 mm solid brick and finely grinded for the Brazilian disc tests. The specimens were then dried in an oven at 40 °C for 48 h until the extra moisture was removed. Figure 1 shows the two types of brick specimens. The densities for the two types of bricks are 1903.5 kg/m^3 and 1960.7 kg/m^3.

The quasi-static tests were conducted on a Shimadzu-300 testing system with reference to ASTM-D3967 [11] (as illustrated in Fig. 1). The failure of each specimen took about 5-10 min which resulted in a strain rate in the split direction of $1.13 \times 10^{-5}\ \mathrm{s}^{-1}$ (measured by the strain gauge). Three specimens for each type of brick were tested at the loading speed. The dynamic split-tensile tests were conducted on the SHPB testing system at the Structural Dynamics Laboratory in Curtin University. The testing system comprises of 100 mm diameter incident bar (5000 mm in length) and transmitter bar (3000 mm in length). The striker bar was also 100 mm in diameter and 500 mm long. The bars are made of high strength tool steel with density of 7800 kg/m^3 and Young's modulus of 200 GPa. Strain gages were glued to the centres of the incident and transmitter bars to monitor stress waves. Figure 2a shows the typical stress wave signal recorded in the incident and transmitter bars. Dynamic equilibrium was checked to ensure the validity of each high-speed compressive test (Fig. 2b). Considering the challenge in predicting the strain rate that a specimen experienced in Brazilian disc test using SHPB system, most researchers utilized loading rate (unit MPa/s from transmitted stress) and some researchers further process the loading rate into strain rate [17]. Equation (1) gives the formula for calculating split-tensile strength. Strain gauges were also glued to the centre of the specimen in the split-tensile direction to monitor specimen strain. The strain rates that specimens experienced were calculated by differentiating the recorded strain time histories, which were validated with those estimated using transmitted stress signal. Both strain rate and loading rate are used to describe dynamic testing results in this study.

$$\sigma_t = \frac{2P}{\pi DL} \tag{1}$$

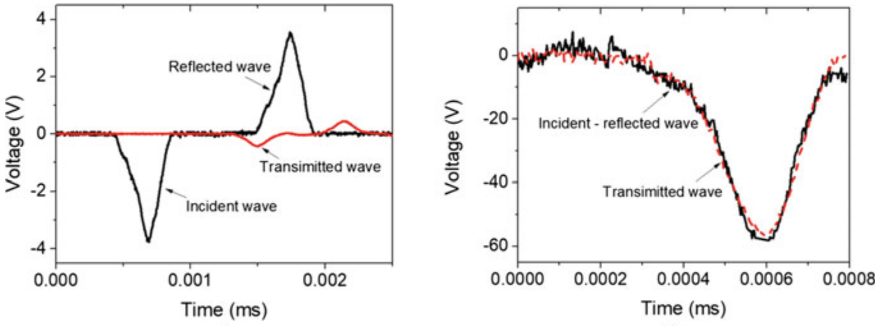
where P is the applied load, D and L are the diameter and length of the specimen.

Table 1 Chemical composition of the bricks from XRF analysis

Brick type	Fe_2O_3	Al_2O_3	SiO_2	MgO	MnO	Na_2O	K_2O	CaO	TiO_2	LOI	OTHER
Limestone Hue	4.1	24.9	59.4	0.3	0	0.4	1.9	0.1	0.8	7.8	0.4
Common Solids	7.3	22	57.2	1.9	0.1	0.7	1.4	0.8	0.9	7.4	0.2

a) b)

Fig 1 Brick specimens: **a** Limestone Hues solid; **b** St common solid

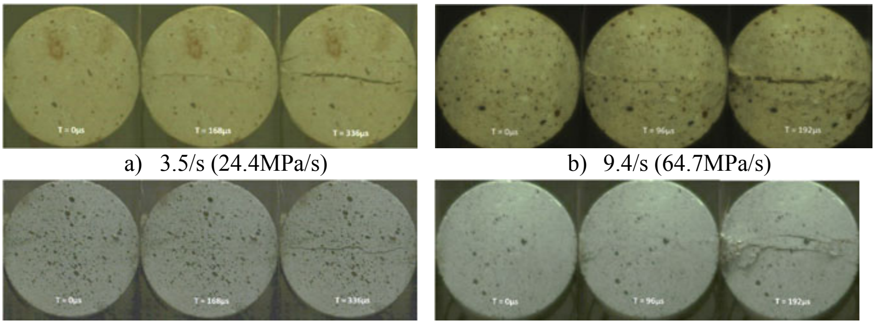


a) b)

Fig 2 **a** Typical stress wave signals; and **b** dynamic equilibrium

3 Results and Analysis

Figure 3 shows the fracturing process of brick specimens, which was recorded using a high-speed camera with a filming rate was 40 kHz. Figure 3a and b show the fracture processes of the limestone hue brick. It is clear that under 3.5/s strain rate at t = 168 μs crack initiated from the centre of the cylinder which grew wider and extended towards both ends of the specimen leading to the failure of the specimen. Under increased strain rate (9.4/s), crack was formed at the centre of the specimen at earlier stage (t = 96 μs) with the contacting end crushed at the left-end of the cylinder. A thorough split failure was formed at 192 μs with both ends of the specimen crushed. Similar fracture processes can be observed on the Common Solids specimens as illustrated in Fig. 3c and d. Because of the dark red colour of the brick, in the dynamic tests the specimens were painted into white colour. It is worth noting that more severe end crushing was observed on the St Common Solids specimen at high strain rate (9.3/s) as well as multiple cracks in the centre of the specimen. This is because of the increased incident wave on the specimen.



a) 3.5/s (24.4MPa/s)

b) 9.4/s (64.7MPa/s)

c) 4.4/s (32MPa/s)

d) 9.3/s (67.7MPa/s)

Fig 3 Dynamic fracture processes of the specimens from high-speed camera images

Tables 2 and 3 tabulate the testing results of the two types of bricks. Typical stress-strain curves of the specimens at different loading rates are shown in Fig. 4. As depicted, both bricks exhibit strong strain rate sensitivity. For the Limestone Hue block, a split-tensile strength of 2 MPa was measured at quasi-static state, which increased apparently as loading rate increased. Under 23.35 MPa/s loading rate, the tensile strength rose to about 3.6 MPa, and at 66.56 MPa/s loading rate the tensile strength further increased to about 7 MPa. The modulus also appears to increase at increased loading rate. Under quasi-static state, a modulus of about 7.6 GPas was measured, which increased slightly to about 7.8 GPa under 23.35 MPa/s loading rate. Under 41.87 MPa/s loading, the modulus further increased to about 8.7 GPa. Similar observation can be found on the Common Solid blocks that both the tensile strength and the modulus measured increased as loading rate is increased. It is worth noting that the failure strain (corresponding to peak tensile stress) of the Common Solid blocks are larger than those of the Limestone Hue blocks, indicating the latter is more brittle.

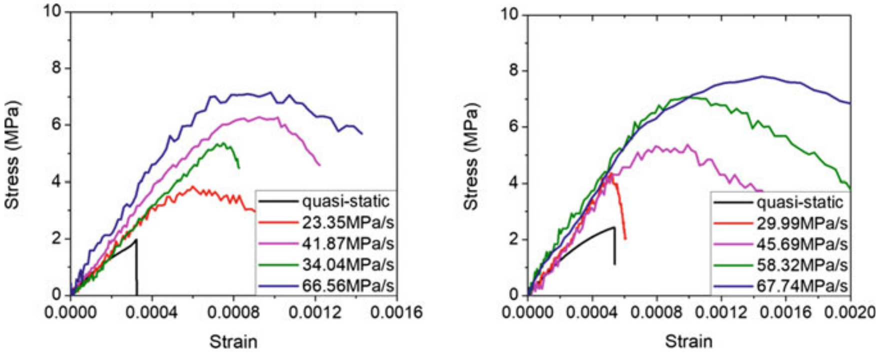
DIF for brick tensile strength are derived by dividing the dynamic tensile strength with the quasi-static strength. Figure 5 shows the tensile DIF vs. strain rate relation for the two types of bricks. It is apparent that the tensile DIF of both types of bricks are strongly strain rate sensitive. For the limestone Hue block, a DIF of around 2.0 was found at around 3.5/s strain rate which increased to about 3.5 at 10/s strain rate. Similar trend but slightly smaller tensile DIF can be observed for the Common Solid blocks. A DIF of about 2.0 was found at about 4/s strain rate which increased to about 3.0 at strain rate of 10/s. The difference is mainly because of the different chemical composition in the two bricks since the specimens were of the same dimension. Available testing data on mortar [1, 9] and concrete [8–10] are also included in Fig. 5 for comparison. As can be found, smaller DIF was measured on mortar by Chen et al. [1] but very close trend between DIF and strain rates like those for the two bricks. Higher DIF on mortar was reported by Ross et al. [9]. The DIFs for concrete by Ross and his co-works [8–10] scatter between 1.0 to 4.0 at strain rate 1/s to 12/s. It was mainly because of different specimen diameters,

Table 2 Testing results for Common Solid

Loading rate GPa/s	Strain rate/s	Tensile strength MPa	Strain	Modulus GPa	DIF (strength)	DIF (modulus)
–	1.13E−05	2.43	5.29E−04	6.40	0.98	0.88
–	1.13E−05	2.32	5.66E−04	7.30	0.94	1.00
–	1.13E−05	2.69	5.28E−04	8.20	1.08	1.12
29.99	4.12	4.35	5.16E−04	8.30	1.75	1.14
32.06	4.4	5.21	6.55E−04	7.30	2.10	1.00
45.69	6.27	5.37	7.92E−04	7.30	2.17	1.00
46.85	6.43	5.74	7.52E−04	7.40	2.31	1.01
48.61	6.67	6.56	9.88E−04	7.20	2.65	0.99
48.8	6.7	6.10	9.02E−04	8.30	2.46	1.14
51.29	7.04	5.77	1.05E−03	8.50	2.33	1.16
53.29	7.32	6.15	9.27E−04	8.20	2.48	1.12
58.32	8.01	7.09	9.63E−04	9.40	2.86	1.29
60.37	8.29	7.61	1.26E−03	8.10	3.07	1.11
67.74	9.3	7.80	1.45E−03	8.60	3.15	1.18
70.48	9.68	7.61	1.05E−03	10.00	3.07	1.37
70.56	9.69	7.06	1.11E−03	8.90	2.85	1.22
79.54	10.92	7.44	1.42E−03	8.10	3.00	1.11

Table 3 Testing results for Limestone Hue

Loading rate GPa/s	Strain rate/s	Tensile strength MPa	Strain	Modulus GPa	DIF (strength)	DIF (modulus)
–	1.13E−05	2.06	4.21E−04	7.60	1.05	1.10
–	1.13E−05	1.86	3.58E−04	6.20	0.95	0.90
–	1.13E−05	1.97	3.14E−04	6.90	1.00	1.00
23.35	3.38	3.63	5.98E−04	7.80	1.85	1.13
24.44	3.54	4.07	7.43E−04	7.80	2.07	1.13
31.43	4.56	3.91	6.41E−04	8.00	1.99	1.16
34.04	4.93	5.24	7.18E−04	7.60	2.67	1.10
41.87	6.07	6.18	9.06E−04	8.70	3.15	1.26
45.10	6.54	5.31	9.47E−04	7.70	2.70	1.12
46.23	6.7	6.55	8.74E−04	8.90	3.34	1.29
53.72	7.79	6.07	1.16E−03	8.30	3.09	1.20
55.58	8.06	6.19	7.64E−04	9.10	3.15	1.32
59.06	8.56	6.79	9.01E−04	8.70	3.46	1.26
60.82	8.81	6.08	9.55E−04	9.40	3.10	1.36
61.72	8.95	7.03	1.23E−03	7.70	3.58	1.12
64.73	9.38	6.74	1.13E−03	9.80	3.43	1.42
66.56	9.65	6.99	9.81E−04	10.90	3.56	1.58
67.25	9.75	6.71	1.06E−03	9.10	3.42	1.32



a) Limestone Hue b) Common Solid

Fig 4 Stress-strain curves of the bricks at different loading speeds

Fig 5 Strength vs. loading rate

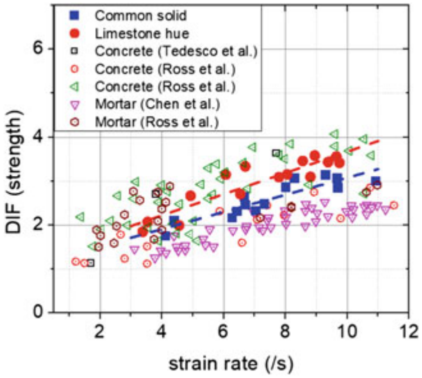
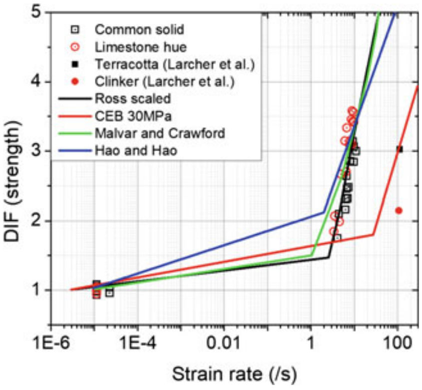


Fig 6 Comparison of DIF with available data



mixtures, and testing methods (Brazilian disc or direct tension). Nevertheless, the overall trends on concrete also agree with the two types of bricks herein.

Figure 6 compares the DIFs of the two types of bricks with available popular tensile DIF-strain rate relations for concrete. As shown, the DIF scatters for bricks from this study aligns with the empirical trendlines by Malvar and Crawford [6] and Ross et al. [8–10]. It is worth noting that Larcher et al. [5] measured a DIF of about 2.2 and 3.0 for Clinker and Terracotta bricks at strain rate of about 100/s through Brazilian disc method using SHPB system. The strain rates were much higher potentially because of much smaller diameter specimens used (40 mm diameter). Further studies covering a wider strain rate range and using different testing methods, i.e. Brazilian split-tension and direct tension are needed and are currently under progress by the authors.

4 Conclusion

This study carried out Brazilian disc tests on two types of clay bricks under quasi-static and dynamic states, which covers strain rate at 1.13×10^{-5}/s to 10/s. It found that the split-tensile properties of bricks are very strain rate sensitive. Significant dynamic increase effect is found on brick strength. The corresponding failure strain and modulus are also found to be strain rate sensitive. Through comparing with existing data on concrete and mortar, it shows that the DIF relations for the two tested bricks are close to the trends by Ross as well as Malvar and Crawford for low strength concrete. Further studies are still needed to confirm existing data on brick and to cover wider strain rate range.

Acknowledgements The authors would like to acknowledge Mr Alf D’Angelo from Midlandbrick, Boral for their support in this study. The financial support from Australian Research Council is also to be acknowledged.

References

1. Chen X, Wu S, Zhou J (2013) Experimental study on dynamic tensile strength of cement mortar using split Hopkinson pressure bar technique. J Mater Civ Eng 26(6):04014005
2. Hao H, Tarasov B (2008) Experimental study of dynamic material properties of clay brick and mortar at different strain rates. Aust J Struct Eng 8(2):117–132
3. Hao Y, Hao H, Zhang X (2012) Numerical analysis of concrete material properties at high strain rate under direct tension. Int J Impact Eng 39(1):51–62
4. Kim D, Sirijaroonchai K, El-Tawil S, Naaman AE (2010) Numerical simulation of the split Hopkinson pressure bar test technique for concrete under compression. Int J Impact Eng 37 (2):141–149
5. Larcher M, Peroni M, Solomos G, Gebbeken N, Bieber P, Wandelt J, Tran NT (2013) Dynamic increase factor of masonry materials: experimental investigations. In ISIEMS-ICPS, Potsdam, Germany

6. Malvar LJ, Crawford JE (1998) Dynamic increase factors for concrete. Retrieved from
7. Pereira JM, Dias A, Lourenço PB (2013) Dynamic properties of clay brick at different strain rates. Paper presented at the Proceedings of the 12th canadian masonry symposium
8. Ross CA, Jerome DM, Tedesco JW, Hughes ML (1996) Moisture and strain rate effects on concrete strength. Mater J 93(3):293–300
9. Ross CA, Tedesco JW (1989) Split-Hopkinson pressure-bar tests on concrete and mortar in tension and compression. Mater J 86(5):475–481
10. Ross CA, Tedesco JW, Kuennen ST (1995) Effects of strain rate on concrete strength. Mater J 92(1):37–47
11. ASTM International, West Conshohocken, USA (2008) Standard test method for splitting tensile strength of intact rock core specimens
12. Xia K, Yao W (2015) Dynamic rock tests using split Hopkinson (Kolsky) bar system–a review. J Rock Mech Geotech Eng 7(1):27–59
13. 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. Constr Build Mater 192:754–767
14. Zhang X, Hao H, Shi Y, Cui J (2015) The mechanical properties of Polyvinyl Butyral (PVB) at high strain rates. Constr Build Mater 93(Supplement C):404–415
15. Zhang X, Hao H, Shi Y, Cui J, Zhang X (2016) Static and dynamic material properties of CFRP/epoxy laminates. Constr Build Mater 114(Supplement C):638–649
16. Zhang X, Zou Y, Hao H, Li X, Ma G, Liu K (2012) Laboratory test on dynamic material properties of annealed float glass. Int J Protective Struct 3(4):407–430
17. Zhou Z, Ma G, Li X (2007) Dynamic Brazilian splitting and spalling tests for granite. Paper presented at the 11th ISRM congress