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A correlation study to support material characterisation of typical Dutch masonry structures

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A R T I C L E I N F O

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A B S T R A C T

To date, several different structural representations of masonry are available for use in the numerical and analytical assessment methods, each calling for a distinct level of refinement regarding the material input. To determine material properties, in terms of strength, stiffness, and toughness under compression, bending, and shear loading, extensive experimental research is necessary. To minimise the burden associated with performing complex and invasive experimental studies, this paper investigated the possible correlations between different material properties, particularly toughness, which received limited attention in past research. The correlation study was mainly conducted on the rich database established from tests on laboratory-made as well as specimens extracted from unreinforced masonry structures built between 1910 and 2010 in the Netherlands. Considering the outcomes of the correlation study, this paper puts forward recommendations to indirectly derive elastic and toughness properties as a function of strength properties. In this way, a complete picture of material properties can be obtained, while minimising the number of experiments and the extent of their invasiveness.

1. Introduction

Reliability of the assessment of existing masonry structures can be improved by well-defined input parameters describing the complete nonlinear response of masonry associated with all the possible local material failures, namely pure crushing, tensile cracking, debonding, shearing along the brick-mortar interface, or any combination of these. To date, several different structural representations of masonry are available for use in the numerical and analytical assessment methods, each calling for a distinct level of refinement regarding the material input. This study focuses on material properties which are required for three types of masonry representations: continuum representations, detailed brick-to-brick models, and structural component-based models. For a more comprehensive overview of masonry representations, the reader is referred to Ref. [1].

The first class, continuum representation, subdivides piers and spandrels into small elements driven by constitutive models at the materials scale (e.g., Refs. [2–4]. The material properties are defined at the masonry level, in terms of stiffness (i.e. Young's modulus and Poisson's ratio), strength (i.e. tensile and compressive strength), and toughness (i.e. fracture energy and shape of the softening branch). Considering that the brick arrangement is responsible for the orthotropic behaviour of the masonry material, continuum damage models often adopt an orthotropic formulation. Consequently, the material properties should be defined at least along the two principal directions, loading perpendicular and parallel to the bed joints.

The second class, detailed brick-to-brick representation, treats piers and spandrels as an assembly of individual constituents, namely bricks, mortar joints, and brick-mortar interfaces (e.g., Refs. [5–10]. The input parameters are no longer described at the level of the masonry as a whole, but at the constituent level. Properties related to cracking and crushing failure of the constituents are generally associated with bricks and mortar, while properties related to shear-sliding and debonding failure are coupled to the brick-mortar interface. This allows considering not only tensile and shear failure at the interface, but also dilatancy effects associated with the uplift upon shearing.

The third class of representations relates to structural component-based models, either analytical or numerical (e.g., Refs. [11–13]. Here, besides compression and shear properties, knowledge of the bending properties of masonry under both in-plane and out-of-plane bending loads is highly relevant. The bending properties can be interpreted as indirect tension, while the abovementioned properties for the continuum and the detailed brick-to-brick representations relate to direct tension.

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In order to characterise the nonlinear response of masonry and its constituents, a large variety of laboratory and in-situ testing methods have been developed in the literature. The former, performed on medium-sized samples, often allows for capturing the complete nonlinear behaviour and thus the full range of material properties. The latter can provide information often only about strength and stiffness. Although in-situ tests are faster with respect to the laboratory test, the accuracy of the results is often of concern (e.g., Refs. [14,15]. Irrespective of the testing methods, a comprehensive characterisation of material properties is often restricted by a lack of financial resources or the need to limit the invasiveness to the structure caused due to sampling or performing in-situ tests.

Generally, practitioners aim to reach a compromise between the damage caused either by extraction of samples or performing in-situ tests, and the knowledge gained in terms of material properties. Therefore, a need exists for developing a framework, though ambitious, which could offer an indirect evaluation of material properties for existing masonry structures. Finding relationships between different material properties can be seen as a gateway to a coherent strategy for material characterisation in support of the assessment of existing structures. By exploring the possible correlations, the burden associated with a comprehensive characterisation of material properties can be reduced and thus time and costs could be saved.

A survey of the literature revealed that some researchers investigated the possible relationships between material properties (e.g. Refs. [16–20], but not in a consistent manner allowing for a comprehensive characterisation of the nonlinear behaviour. Apart from literature, Eurocode 6 [21] provides brief insights into the relationship between the compressive strength and the Young's modulus of masonry, and implicitly gives the ratio between the vertical and horizontal out-of-plane bending strength of wallets. However, investigating the correlations between the key input parameters, such as fracture energy in compression, bending, and shear, has been received only little attention in the literature and international/national standards.

Aiming to formulate a strategy for material characterisation of existing masonry, which is currently missing in the literature/design codes, this paper presents a correlation study to predict the stiffness and toughness properties of masonry under compression, tension and shear as a function of strength properties, easy-to-obtain properties. This is achieved, in light of the comprehensive database for typical Dutch masonry structures established from tests on medium-sized samples in the form of wallets and triplets, which were either field-extracted or laboratory-made.

2. Experimental programme

The material properties used for the correlation studies were determined through an extensive experimental campaign in support of seismic assessment of unreinforced masonry structures in the Groningen region, located in the north west of the Netherlands, with respect to the induced seismicity. Fig. 1 presents an overview of the adopted testing programme, whereby the nonlinear response of a wide variety of masonry types in terms of strength, stiffness, and toughness under compression, bending, and shear loading was investigated. Compression properties of masonry, in terms of strength, Young's modulus, and compressive fracture energy, were characterised by compressing wallets along the two directions: loading perpendicular to the bed joints, referred as vertical compression (Fig. 1a); and loading parallel to the bed joints, denoted as horizontal compression (Fig. 1b). Bending properties of masonry in terms of flexural strength and bending fracture energy were characterised as wallets were bended over two configurations: four-point bending test with the moment vector parallel to the bed joints and in the plane of the wall, denoted as vertical out-of-plane bending test (Fig. 1c); four-point bending with the moment vector orthogonal to the bed joints and in the plane of the wall, denoted as horizontal out-of-plane bending test (Fig. 1d). Apart from bending tests, bond wrench tests on stack-bonded prisms were performed to evaluate the bond strength along the unit-mortar interface (Fig. 1e). Shear properties along

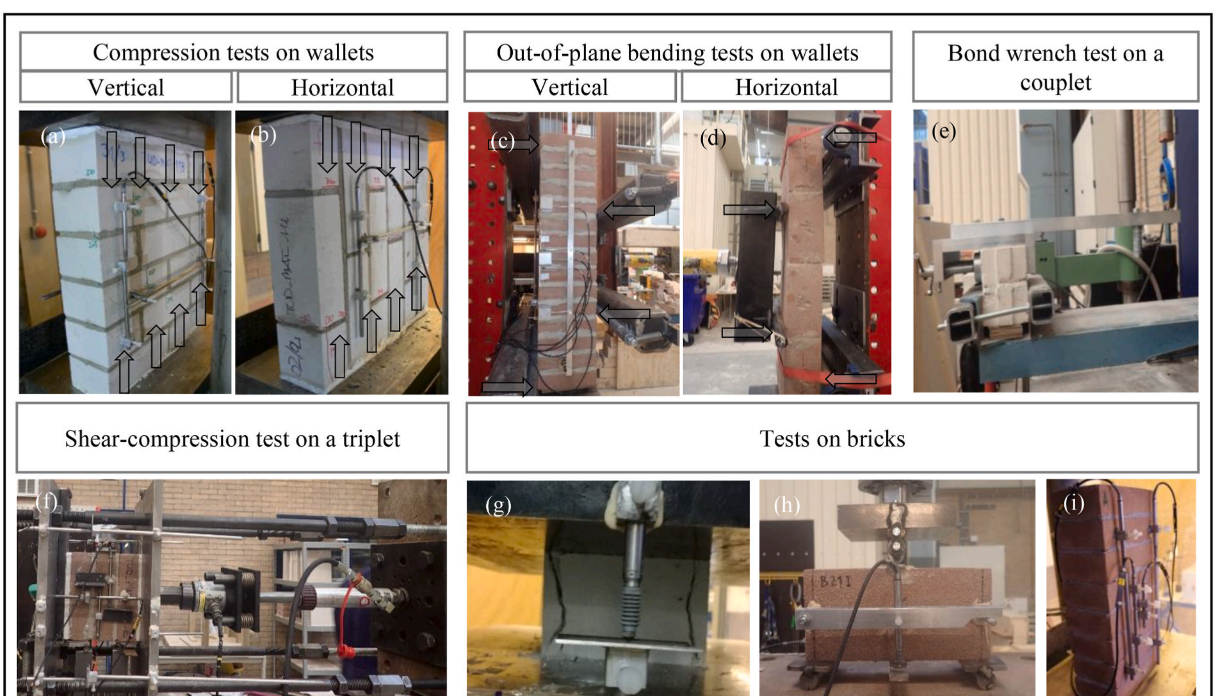

Fig. 1. An overview of testing campaign: (a,b) vertical and horizontal compression tests; (c,d) vertical and horizontal four-point out-of-plane bending tests; (e) bond wrench test; (f) shear-compression test; (g) compression test on a single brick; (h) three-point out-of-plane bending test on a brick; (i) compression tests on a stack-bonded prism.

Table 1
Overview of the number of tested specimens, number of objects, and the typical dimensions of specimens. Number of objects refers to tests on different masonry types.

Type of test		No. specimens	No. objects	Dimensions in mm^3		
				Brick masonry Single-wythe	Brick masonry Double-wythe	CS element Single-wythe
Compression	Vertical	118	27	430 × 475 × 100	540 × 650 × 210	1283 × 1290 × 100
	Horizontal	49	11	430 × 475 × 100	540 × 650 × 210	1283 × 1290 × 100
Bending	Out-of-plane_ Vertical	40	9	430 × 600 × 100	760 × 900 × 210	1350 × 1950 × 100
	Out-of-plane_ Horizontal	59	17	880 × 300 × 100	1200 × 650 × 210	2300 × 1300 × 100
	Bond wrench	152	23	210 × 80 × 100	210 × 80 × 100	120 × 220 × 100
Shear-compression test		230	28	210 × 180 × 100	210 × 180 × 100	300 × 300 × 100

the unit-mortar interface, in terms of cohesion, friction coefficient, and mode-II fracture energy, were evaluated as triplets/couplets were subjected to shear-compression loading (Fig. 1f). In addition, compressive strength and flexural strength of units were determined by performing compression (Fig. 1g) and three-point bending tests, respectively (Fig. 1h). To determine the unit Young's modulus, compression tests on stack-bonded prism were conducted (Fig. 1i), as suggested by Ref. [22]. Generally, the outlines of the European standards were mainly followed when deciding on the samples' dimensions and loading rate. Table 1 provides an overview of the number of tested specimens and their dimensions. For the sake of conciseness, the descriptions of the testing procedure and data elaboration are not reported herein, however a list of the supporting technical reports is provided in Table 2. For additional information reader is referred to these documents.

The material properties used in this study were obtained from tests on both laboratory-made and field-extracted medium-sized samples. As expected, extracting a complete set of samples from existing buildings is almost impossible; for example, the complete characterisation of masonry with nominal brick dimensions of 210 × 71 × 100 mm requires the extraction of samples for approximately 11 m^2, which correspond to a wall with dimensions of 4000 × 2700 mm. In return, replicating masonry allows for carrying out a complete study of the material response independent of the sample size. As a result, for the five most typical Dutch masonry types, the entire set of specimens required to characterise the compression, bending, and shear behaviour of masonry was replicated in the laboratory at Delft University of Technology. Moreover, this research further benefited from performing tests on field-extracted samples. In this context, from fifteen different unreinforced masonry dwellings and schools in the Groningen region, built between 1910 and 2010, samples were extracted and packed and then transported to the laboratories of Delft University of Technology and Eindhoven University of Technology [28]. During the inspection and the sampling from each building, more than one masonry type was often identified because of the extension of the building during different periods, the use of different materials, and variations in masonry quality within a wall or between different walls. Accordingly, further divisions for these building were made to consider such differences. As a result, we made 29 sub-divisions of masonry types, treating each as a separate object. Thus, throughout this paper 'object' refers to the different masonry types. This research included both brick masonries with conventional joints (such as single-wythe solid clay brick masonry, double-wythe solid clay brick masonry, single-wythe perforated clay brick masonry, and single-wythe calcium silicate brick masonry) and large element masonry with thin-layer joints (such as single-wythe calcium-silicate element masonry).

Table 2
An overview of references, where the material properties are extracted for the correlation studies.

Data collection	Reference
Lab-made calcium silicate brick masonry and perforated clay brick masonry	[23]
Lab-made solid clay brick masonry, both single- and double-wythe	[24]
Lab-made calcium silicate element masonry	[25]
Field-extracted calcium silicate brick masonry and clay brick masonry	[26–29]

3. Correlation study

This section investigates the presence of a link between different material properties. To this end, one material property is first plotted against a predictor variable. To predict the relationship between the two variables, linear regression analysis, often forced to pass the origin, is conducted. To quantify the accuracy of the relationships, values of the correlation of determination (R^2) are also presented. Note that the negative value of the correlation of determination means that the chosen linear model did not follow the trend of data.

To estimate the minimum number of masonry types required for an 80% chance of finding a statistically significant correlation, an a priori power analysis using G*Power 3.1 software [30] was conducted. Considering the desired level of significance (α=0.05) and a medium effect size [31], 67 data points would be required. However, at best, 28 masonry types were treated in this study, including both the laboratory-made and field-extracted objects. Through a post hoc power analysis, it was determined that by using 28 data points the chance of finding a statistically significant correlation would be 46%. This means that there is a medium chance that the relationship found between two variables exists and that is not due to chance. This highlights the need for further studies to obtain more observations. For this reason, the data used in this research are available in an open-access database for future research.

Although comparisons with other correlation rules from the literature and codes are included in this section, these were not incorporated into the correlation study, as the specimens' dimensions and testing conditions, i.e. their boundary conditions and loading rates, could differ. The literature data were presented when the material properties of at least three different masonry types were reported, thus allowing us to conduct a regression analysis. The literature review, used to examine the applicability of the established relationships, is mainly built on the following references:

- [16] who reported the findings of an extensive joint research and development project in the Netherlands (based on CUR Report 171, 1994). This paper benefits from the results of an experimental campaign on laboratory-made masonry at material-scale, which were mainly written by van der Pluijm and A.Th. Vermeltfoort.
- Outlines of the New Zealand Society for Earthquake Engineering (NZSEE), as well as experimental studies in their support by Refs. [19,20]; and [32]. These researchers investigated the relationships between flexural bond strength, shear strength, and compressive strength of masonry and mortar for historical clay brick masonry structures. The experimental data were obtained from in-situ tests as well as laboratory tests.
- A study by Ref. [33]; who reviewed expressions in the literature for deriving material properties. However, some of the suggested expressions were borrowed from the literature on concrete, and they were not experimentally verified for masonry.
- Findings from Ref. [34]; who exhaustively discussed the relationship between different material properties of typical masonry in South Africa, namely conventional concrete masonry (CON), geopolymer masonry (GEO), compressed-stabilised earth masonry (CSER), and

Table 3
Ratio between properties of mortar (Young's modulus, E_{m3}, compressive strength, f_m, flexural strength, f_{bm}, and tensile strength, f_{tm}). Correlation of determination in parentheses.

Reference	E_{3m}/f_m	f_{bm}/f_m	f_{tm}/f_m
[16]	155 (−0.73)	0.15 (0.85)	–
[22]	97 (0.58)	–	–
[39]	869 (0.68)	–	–
[18]	200 (0.90)	–	–
[40]	–	0.14–0.23	0.03–0.05
[34]	319 (0.90)	–	–
[41]	57 (0.97)	–	–
[42]	157 (0.55)	0.19 (0.81)	–
This work	239 (–)*	0.32 (0.83)	–

* Only from tests on one type of mortar used for replication of samples.

adobe (ADB) [34]. seemed not yet to pay much attention to the statistical measure of the strength of the relationships.

3.1. Mortar properties

Characterising the material properties of mortar in existing structures is often acknowledged as a challenging task. Up to now, researchers have deployed a number of techniques to estimate the compressive strength of mortar, either using laboratory tests on extracted mortar, such as the double punch test, or using semi- or non-invasive in-situ testing methods, e.g., the penetrometer test and Helix pull-out test. In this framework, the double punch test can be regarded as the most common testing method, and it is proposed by the German standard [35]. Following this method, intact pieces of mortar, though it is not always technically feasible to extract them, are subjected to compression loading. However, it turns out that the testing results should be interpreted with caution, as they depend on the thickness of the mortar (e.g., Refs. [36,37]. The calibration of the testing results on mortar strength became more challenging, as the results of the double punch tests on mortar extracted from joints and those obtained from the standard tests on cubic mortar casted in mould did not show satisfactory agreement [38]. Such a difference could be expected, as the curing conditions for the two types of mortar samples are different. Considering the limitations of the available testing methods, as expected, the pool of experimental data on the properties of existing mortar is limited in the literature; in this research, we only characterised the properties of mortar used for the replication of samples in the laboratory with the standard mortar prism tests. To evaluate the Young's modulus of mortar, researchers either performed compression tests on casted mortar prisms, or indirectly found it from tests on masonry wallets, e.g., Ref. [22]. Insight into the tensile behaviour of mortar can be gained by performing a direct tensile test. However, due to the difficulties encountered during the application of direct tensile tests, three-point bending tests are more popular and widely accepted among the masonry research community.

Table 3 lists the ratio between the elastic modulus, E_{3m}, and the compressive strength of mortar, f_m, as well as the ratio between flexural strength, f_{bm}, and the compressive strength of mortar, f_m, found from linear regression analysis. A wide ratio, ranging between 57 and 869, was found between the Young's modulus and mortar compressive strength. In this study, we found a ratio of 239 for one mortar type, in agreement with the findings of [18,34]; and [42]. A ratio lower than 100 was found by Refs. [22,41]; while [39] suggested a much higher ratio, 869. Among the aforementioned studies, only [16,42] reported the values of mortar flexural strength. In this study, we found a ratio of 0.32 between the flexural strength and compressive strength of mortar, which is higher than the findings in the literature. Concerning the tensile properties of mortar [40], performed both three-point bending and uniaxial tests on iron ore tailing mortar. Though the mortar type is different, the ratio between the flexural strength and compressive of mortar ranged from 0.14 to 0.23, similar to the literature data. However, a lower ratio of tensile strength to compressive strength of mortar was found, ranging from 0.03 to 0.05.

Table 4
Ratio between properties of units (Young's modulus, E_{3b}, normalised compressive strength, f_b, flexural strength, f_{bb}, and tensile strength of units, f_{tb}). Correlation of determination in parenthesis.

Reference	Unit type	E_{3b}/f_b	f_{bb}/f_b	f_{tb}/f_b
[45]	Clay brick, CS brick	–	–	0.03–0.05 (0.70)
[16]	Clay brick, CS brick	266 (0.58)	–	0.04–0.07
[44]	Clay brick	–	–	0.05
[22]	Clay brick	430 (0.81)	–	–
[18]	Clay brick	300 (0.39)	–	–
[33]	Historical	350	–	0.12–0.14
[34]	CON, GEO, CSER, ADB	911 (0.36)	0.02 (0.65)	–
NZSEE	Clay brick	–	–	0.12 (1.0)
This work	Clay, CSB, CSE	–	0.11–0.45	–

3.2. Unit properties

Few studies have investigated the relationship between the material properties of units in a systematic way. A compression test on a unit is easy to perform; however, in most cases the compressive strength is the only property that has been quantified. To assess the brick elastic modulus [22], proposed performing a compression test on a pile of bricks bonded together with a very thin layer of stiff material. This study applied the same method for the new production of units. The limited

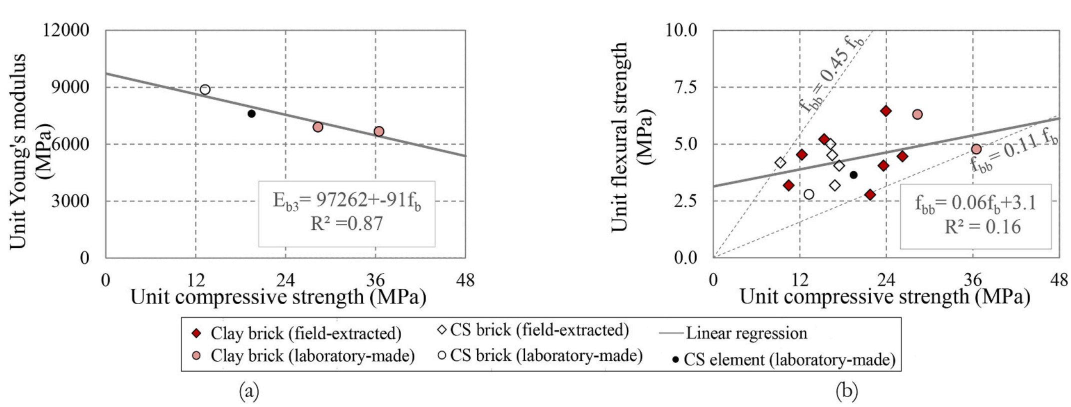

Fig. 2. Correlation between unit compressive strength and: (a) unit Young's modulus; (b) unit flexural strength.

number of units extracted from existing buildings did not allow us to build stack-bonded prisms and thus measure the elastic modulus. Apart from this testing method, some researchers (e.g. Refs. [14,34], adopted the procedure recommended by standard EN 12390-13 (CEN 2019) to assess the Young's modulus of concrete, in which the compressive load is applied parallel to the stretcher face of the brick. However, as reported by Ref. [43]; due to the heterogeneous nature of brick, the stiffness differed along the two principal directions. To evaluate the tensile response of a unit, direct tensile tests can be performed that require more effort in terms of preparation and testing set-up [33,44]. Thus, researchers adopted the wedge splitting test or three-point out-of-plane bending tests to evaluate unit tensile properties.

The values of the elastic modulus of units versus the compressive strength of units found in this study are plotted in Fig. 2a, showing a decreasing trend in the Young's modulus with an increase in compressive strength. This relationship, based on limited number of data, contrasts with previous studies, in which an upward trend was found, see Table 4. Generally, previous studies found an average ratio of 266–450, with the exception of [34]; who found a higher ratio for typical units in South Africa; however, these differ substantially in terms of material composition and dimension from the typical Dutch units used in this study. Note that the values of the Young's modulus listed in Table 4 were evaluated in the stretcher direction, meaning that the compression load was applied perpendicular to the bed face.

The values of unit flexural strength, obtained from bending tests, f_{bb}, versus the normalised compressive strength of units, f_b, found in this study are plotted in Fig. 2b. No specific relationship is found, as the results are widely scattered, and the ratio between unit flexural strength and compressive strength varies between 0.11 and 0.45 (dashed lines in Fig. 2b). For the typical South African unit [34], found a ratio of 0.02, see Table 4.

A difference can be expected between the direct tensile strength of a unit, f_{tb}, and the flexural strength obtained from the bending tests, f_{bb}. Hence, in Table 4 we made a division between these two properties. The ratio between the tensile strength, f_{tb}, and the unit normalised compressive strength, f_b, is reported in Table 4. A lower ratio was reported in the literature when considering the tensile strength rather than the flexural strength of a unit. In the literature, the ratio between the tensile strength and compressive strength of units ranged from 0.03 to 0.14.

3.3. Masonry compressive strength

The compressive strength of masonry is regarded as the most central mechanical property for the design and safety assessment of existing structures. However, in practice, only minimal intrusion into the building functionality is allowed, if any, and the possibility of extracting large masonry samples is highly limited. As a result, attempts have been made in the literature to associate the compressive strength of masonry with the mechanical properties of masonry constituents, as the extraction of individual units and mortar is not as invasive as the extraction of a large sample.

Postulating a series of assumptions, researchers introduced a large variety of predictive models, from simple linear models with one variable up to complex nonlinear models incorporating the effects of multiple variables [46,47]. proposed linear models, while nonlinear expressions were introduced by, for example Eurocode 6(CEN 2005), [18,48]; correlating the compressive strength of masonry with the compressive strength of the masonry units as well as the compressive strength of the mortar. In most instances, the proposed expressions in the literature did not account for any divisions based on the masonry. However, some researchers including [49]; proposed two empirical formulas, depending on the bonding pattern of masonry and thus the thickness. Apart from the compressive strength of masonry constituents, researchers such as [50] proposed a mathematical model to account for the slenderness ratio (height to thickness ratio) as well as the volume fraction of a unit, VF_b, and the volume ratio of bed joint to mortar, VR_{mh}. Table 5 lists a summary of the proposed equations in the literature, where f_b and f_m are the normalised compressive strength of masonry units and the compressive strength of mortar, respectively. It should be emphasised that unlike the literature, Eurocode 6(CEN 2005) refers to the characteristic compressive strength of the masonry rather than the mean value. However, as suggested by standard [53]; the ratio between the mean value and the characteristic value of masonry compressive strength can be assumed to be 1.2, if fewer than five specimens were tested. Mean properties are often used for the assessment of existing structures, while design values are adopted when dealing with new structures.

Table 5
Overview of a selection of expressions in the literature to calculate either the mean value of masonry compressive strength, f'_m, or characteristic compressive strength, f'_k, using compressive strength of mortar, f_m, and normalised compressive strength of unit, f_b.

Reference	Model	Description
Eurocode 6 [21]	$f'_k = 0.55 f_b^{0.70} f_m^{0.30}$	Valid for clay and CS brick*
	$f'_k = 0.80 f_b^{0.85}$	Valid for CS element masonry
[49]	$f'_m = 0.317 f_b^{0.531} f_m^{0.208}$	Valid for clay brick masonry
[18]	$f'_m = 0.63 f_b^{0.49} f_m^{0.32}$	Calibrated for stack-bonded clay brick masonry
[51]	$f'_m = 1.242 f_b^{0.531} f_m^{0.208}$	Valid for single-wythe masonry wallet
	$f'_m = 0.334 f_b^{0.778} f_m^{0.234}$	Valid for double wythe masonry wallet
[50]	$f'_m = \frac{0.54 f_b^{1.06} f_m^{0.004} VF_b^{3.3} VR_{mH}^{0.6}}{H/t^{0.28}}$	Calibrated for single-wythe clay brick masonry prism
[52]	$f'_m = 0.91 f_b^{0.33} f_m^{0.67}$	Calibrated for single-wythe clay brick masonry wallets

* Valid for Group 1 with general purpose mortar.

The error between the predicted and experimental values is shown in Fig. 3. The analysis was made only for the laboratory-made masonry types with known properties of mortar. In general, the analytical expressions tend to underestimate the values of masonry compressive strength. In order to define the best model proposed in literature, the error is calculated for each expression. The lowest and the highest errors are associated with the models proposed by Eurocode 6 [21,49]; respectively. Accordingly, although a variety of models were introduced in the literature, the model introduced in Eurocode 6(CEN 2005) still can be considered the most reliable one for the analysed cases.

3.4. Young's modulus of masonry

Establishing a correlation between the Young's modulus and compressive strength of masonry is of great interest, as it could reduce the amount of effort required to accurately measure longitudinal deformations. National standards often introduce a linear expression

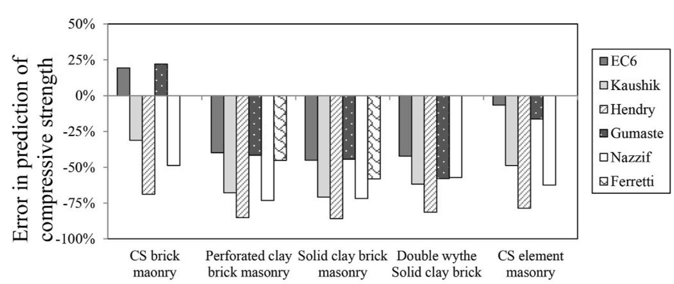

Fig. 3. Error between the predicted mean values of masonry compressive strength obtained from the literature equations and the experimental results for laboratory-made masonry types.

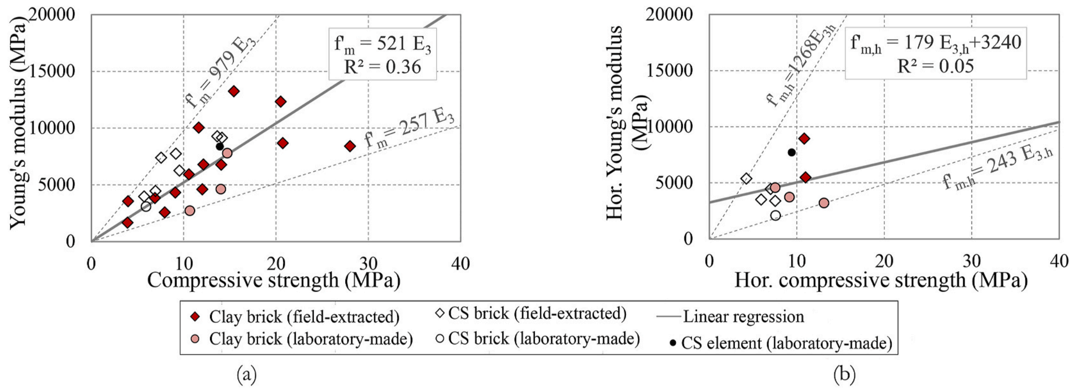

Fig. 4. Relationship between Young's modulus and mean values of compressive strength under: (a) vertical compressive load; (b) horizontal compressive load.

Table 6
Ratio between the Young's modulus, E_3, and mean value of compressive strength, f'_m, as well as characteristic compressive strength of masonry, f'_k, under a vertical loading configuration. Correlation of determination in parentheses.

Reference	Masonry type	$k_m = E_3/f'_m$	$k_k = E_3/f'_k$
[16]	Clay and CS brick masonry	526 (0.80)	–
[22]	Clay brick masonry	304 (0.88)	–
[51]	Clay brick masonry	425 (0.91)	
[18]	Clay brick masonry	550 (0.63)	–
[20]	Clay brick masonry	290 (0.76)	–
[54]	Clay brick masonry	–	85-230 (0.46)
[34]	Typical South African	–	1951 (0.88)
Eurocode 6 [21]	No division	–	1000
NEN 6790	Dutch masonry	–	700
NZSEE	Clay brick masonry	300	–
This work	Clay brick masonry	477 (0.42)	575 (0.28)
	CS brick masonry	702 (0.79)	833 (0.19)
	CS element masonry	602 (–)	686 (–)
	All masonry types	521 (0.36)	624 (0.16)

between the Young's modulus and the mean values of masonry compressive strength or characteristic compressive strength. Eurocode 6 [21] recommended a linear relationship, with the elastic modulus of masonry to be evaluated as 1000 times higher than the characteristic compressive strength of masonry, i.e. k_k=1000. However, supplementary information is often available in national annexes for each country; a value equal to 700 was suggested for the Dutch masonry, NEN 6790 (2005). Unlike Eurocode 6 [21], NZSEE and the majority of studies in the literature investigated the ratio between the Young's modulus and the mean values of compressive strength, k_m, rather than the characteristic value, k_k.

Variations in the Young's modulus with respect to the mean values of compressive strength obtained under a vertical configuration are plotted in Fig. 4a. Through the regression analysis of 26 different Dutch masonry types, a ratio of 521 was obtained, though the correlation of determination was relatively low (R^2=0.36). However, a breakdown of the data based on the masonry types, as listed in Table 6, revealed a higher ratio for the CS brick masonry wallets, 702, than for clay brick masonry, which had an average ratio of 477. Moreover, the results of the literature studies are set out in Table 6, which lists the ratio between the Young's modulus and the mean values of compressive strength, k_m. In the literature, values of k_m ranged from 300 to 526. The upper limit is in line with the ratio of 521 that we found by considering all masonry types. Table 6 also lists the ratio between the Young's modulus and characteristic compressive strength, k_k, found in this study and reported in the literature. Considering all masonry types studied in this research, a ratio of 624 was found. It can be seen that NEN 6790 [55] provides an acceptable estimate of the Young's modulus, although it slightly overestimates the value of the Young's modulus for clay brick masonry.

Variations of the Young's modulus with respect to the mean values of compressive strength obtained under horizontal configuration are plotted in Fig. 4b. It can be seen that the data are quite scattered and the ratio of the horizontal Young's modulus to horizontal compressive strength ranged from 243 to 1268. The simple linear regression analysis indicated that no clear relationship exists between these two properties (R^2=0.05). However, this could be influenced by the limited amount of data.

3.5. Strain corresponding to masonry compressive strength

So far, there has been limited discussion about the indirect estimation of the strain corresponding to masonry compressive strength,

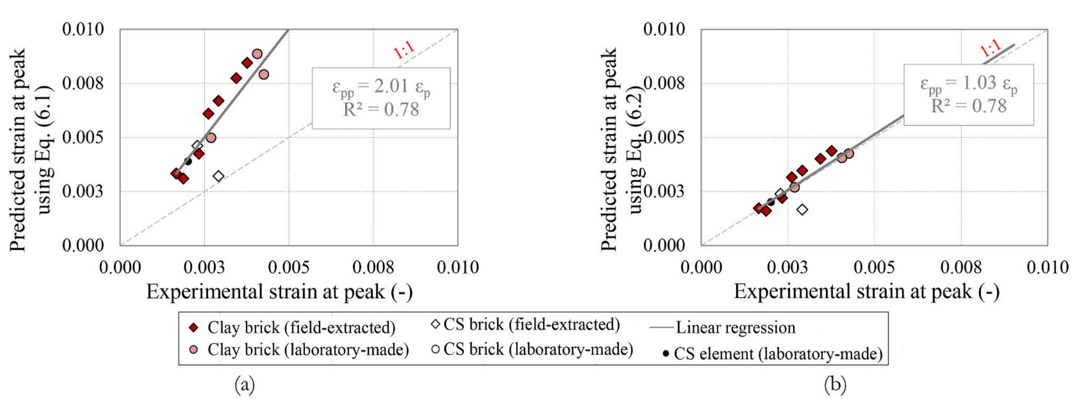

Fig. 5. Relationship between the experimental values of peak strain, ε_p, and the predicted value, ε_{pp}, using: (a) the equation introduced by Ref. [18] for stack-bonded specimens; (b) the equation calibrated in this study for wallets.

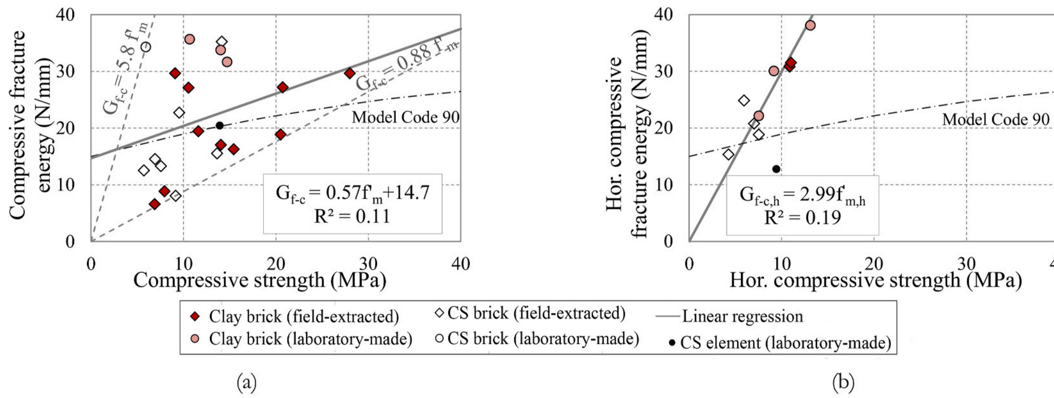

Fig. 6. Relationship between compressive fracture energy and compressive strength of masonry under: (a) vertical configuration; (b) horizontal configuration.

referred to as peak strain. In this context [18], introduced an expression in which the predicted peak strain, ϵ_{pp}, of a stack-bonded prism is a function of the mortar compressive strength, f_m, the masonry compressive strength, f'_m, and the elastic modulus of masonry, E_3, as follows:

$$\epsilon_{pp} = \frac{0.27 f'_m}{E_3^{0.7} f_m^{0.25}} \tag{1}$$

The proposed model by Ref. [18] leads to an overestimation of the values of peak strain for the wallets studied in this research; as shown in Fig. 5a, a ratio of 2.01 was found between the peak strain and the predicted values. In this figure, the experimental data obtained for the laboratory-made wallets are supplemented with calculated data for the field-extracted masonry by calculating the compressive strength of mortar as 1/0.036 of the flexural bond strength. This expression was proposed by Ref. [19]; and its validity for the studied data set is presented in Section 3.7.

To improve the accuracy of the predicted values of peak strain, an attempt was made to calibrate the coefficients of Eq. (1) using the data obtained in this study from tests on wallets. An acceptable agreement between the predicted values and the experimental data was found in Fig. 5b, using the following revised equation:

$$\epsilon_{pp} = \frac{0.18 f'_m}{E_3^{0.73} f_m^{0.20}} \tag{2}$$

3.6. Compressive fracture energy of masonry

Several researchers, e.g., Ref. [33]; have argued that the compressive fracture energy of masonry should be treated as a structural property rather than a true material property, as it is measured upon the formation of multiple cracks and not a single crack. Nevertheless, in finite element softening macro-models, the compressive fracture energy along with some crush bandwidth parameters is required to achieve mesh-objective results. Also, the original experimental work by Ref. [56] on concrete clearly showed that compressive stress-displacement curves were objective for different specimen lengths, while stress-strain curves were non-objective.

A systematic understanding of the gradual decrease of masonry compressive resistance in the softening phase is still lacking. In the absence of data on the post-peak behaviour of masonry, scholars such as [57] recommended the use of the parabolic curve proposed by Model Code 90 [58] for concrete to model the nonlinear behaviour in compression, as in Eq. (3). The proposed model to predict the compressive fracture energy of masonry, $G_{f\text{-}cp}$, reads only the compressive strength of masonry, f'_m, and is applicable only for masonry with a compressive strength between 12 MP and 80 MPa.

$$G_{f-cp} = 0.15 + 0.43 f'_m - 0.0036 \left(f'_m\right)^2 \tag{3}$$

In this framework [57], introduced the concept of the ductility index, which is defined as the ratio of compressive fracture energy ($G_{f\text{-}c}$) to the value of masonry compressive strength (f'_m) [57]. recommended the values of average ductility index as 1.6 mm and 0.68 mm, respectively, for masonry with mortar compressive strength lower than 12 MPa and between 12 and 80 MPa. In the present study, the average value of the ductility index for masonry with a mortar strength lower than 12 MPa was found to be 1.9 mm, which is comparable with the value of 1.6 mm suggested by Ref. [57]. However, for masonry with a mortar strength higher than 12 MPa, the average value of the ductility index was found to be 1.5 mm, almost two times higher than the one recommended by Ref. [57].

For the masonry types analysed in this research, neither the parabolic equation of Model Code 90 (CEB-FIP 1990) nor the linear function could accurately show the relationship between the compressive

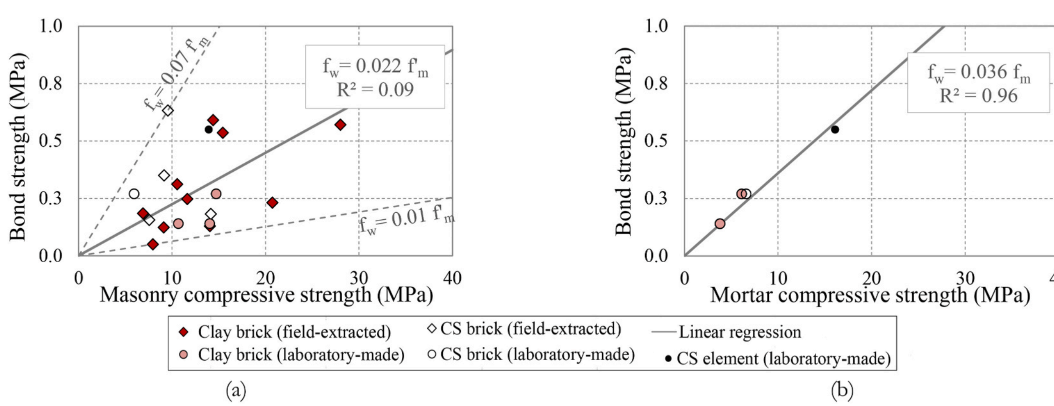

Fig. 7. Correlation between bond strength and: (a) masonry compressive strength; (b) mortar compressive strength.

Table 7
Ratio between the bond strength, f_w, and compressive strength of masonry, f'_m, and of mortar, f_m. Correlation of determination in parentheses.

Reference	Masonry type	f_w/f'_m	f_w/f_m
[39]	Clay masonry	0.065 (0.31)	0.012–0.077
[60]	Soil-cement masonry	0.033 (0.10)	0.035 (0.35)
[19],*	Clay brick masonry (field-extracted)	0.012 (0.89)	0.031 (0.82)
[61]	Clay masonry	0.130 (0.11)	0.05–0.14
[62]	Clay masonry	–	0.034 (0.88)
This work	All masonry types	0.022 (0.09)	0.036 (0.96)**

* Values reported by Ref. [19] are re-calculated excluding the outliers.
** The ratio is obtained by considering only the laboratory-made masonry types.

fracture energy and the compressive strength of masonry along the two loading directions, as shown in Fig. 6a for vertical compression and Fig. 6b for horizontal compression. A wide ratio, ranging from 0.88 to 5.8, was found between the compressive fracture energy and the compressive strength of masonry wallets under vertical compressive load, Fig. 6a. The regression analysis indicated no linear relationship between these two properties. Unlike vertically compressed wallets, the values for horizontal compressive fracture energy are more concentrated along the linear regression line, and thus are less scattered than the values for vertical compressive fracture energy, Fig. 6b. Such differences could be explained by the different failure modes. The failure of the vertically compressed wallets showed various forms of brick tensile failure or shear failure, while failure in the horizontally compressed wallets consistently occurred in one form, namely interface debonding.

3.7. Bond strength

Since the bond wrench test has the advantage of both simplicity and repeatability with minimum intervention in building functionality [59], finding relationships between the values of bond strength, measured using the bond wrench test, and the compression properties of mortar/masonry is of particular interest. To this end, Fig. 7 shows the relationships between the bond strength and the compressive strength of masonry as well as the compressive strength of mortar obtained in this research from tests on laboratory-made and field-extracted masonry types.

The very low correlation of determination value (R^2=0.09) proves that there is not a linear relationship between the bond strength and compressive strength of masonry for the studied masonry types, Fig. 7a. The dashed lines show a wide ratio between the bond strength and compressive strength of masonry, varying from 0.01 to 0.07. The very low correlation of determination value obtained from the regression analysis (R^2=0.09) proves the absence of a relationship between the bond strength and masonry compressive strength. Apart from the studied masonry types, Table 7 lists the ratio between the bond strength and masonry compressive strength reported by several researchers; the values in parentheses are the coefficient of determination. Generally, researchers found very low values for the correlation of determination over a broad range, varying from 0.005 to 0.065, thus confirming the conclusion of the current research. However [19], reported a strong relationship with a ratio of 0.012 obtained from tests on historical clay brick masonry types in New Zealand.

Unlike the compressive strength of masonry, an acceptable correlation with a strong relationship (R^2=0.96) was found between the bond strength and the compressive strength of mortar for laboratory-made specimens, Fig. 7b. Although this correlation was found based on the analysis of a limited number of masonry types, the obtained ratio of 0.036 is comparable to those reported by Refs. [19,60,62] as shown in Table 7. However, it should be noted that [39,61] reported very low values for the correlation of determination, indicating the absence of a linear relationship between the mortar compressive strength and bond

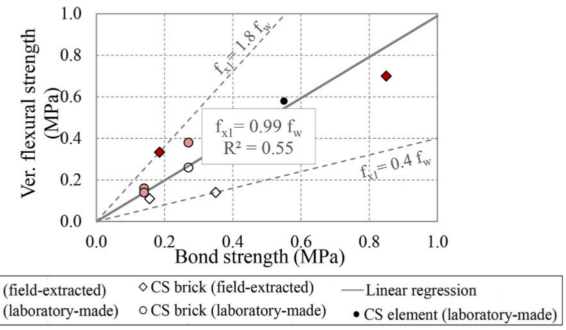

Fig. 8. Correlation between flexural strength of masonry obtained from vertical out-of-plane bending tests and bond strength obtained from bond wrench tests.

strength.

From a physical point of view, a link could be expected between the bond strength obtained from the bond wrench test and the flexural strength of wallets determined by the vertical bending test with the moment vector parallel to the bed joints and in the plane of the wall. In both tests, the failure often occurred along the brick-mortar interface in the bed joint plane, and thus these strength parameters depend on the brick-mortar interface strength. Fig. 8 shows a moderate correlation (R^2=0.55) between these two properties, for which a ratio of 0.99 was found. As seen in the graph, the widely dispersed values belonged to the field-extracted masonry types, while a better correlation was observed for the laboratory-made masonry than for the field-extracted masonry. Several researchers also reported a one-to-one correspondence between the vertical flexural strength and the bond strength of masonry, e.g., Ref. [82].

3.8. Cohesion

No clear link between the compressive strength of masonry and cohesion was found in this study, which accords with the findings of previous studies. The values of cohesion versus the masonry compressive strength obtained in this research from tests on laboratory-made and field-extracted masonry types are plotted in Fig. 9a. The very low correlation of determination (R^2=0.02), obtained from the regression analysis of all masonry types, indicates the absence of a linear relationship between these two properties, Fig. 9a. As seen in the graph, data are very scattered, and the ratio between the cohesion and masonry compressive strength ranged from 0.002 to 0.07 (dashed lines in Fig. 9a). In addition, Table 8 lists the breakdown of these ratios for different masonry types, though this division does not lead to an improvement in the correlation of determination (presented in parentheses).

As shown in Fig. 9b, the very low value of correlation of determination (R^2=0.03) indicates that there was no clear relationship between the mortar strength and cohesion. A wide ratio was found between these two properties, ranging between 0.01 and 0.13 (dashed lines in Fig. 9b). Note that the database was augmented to include the data from existing masonry, for which the mortar compressive strength was calculated from the bond strength (Section 3.7). The significant influence of mortar compressive strength on cohesion was previously investigated by several researchers. However, it can be concluded that apart from the mortar strength, the brick and mortar composition, the physical characteristics of bricks, such as surface roughness, and the water retention of bricks and mortar can largely influence the quality of the bond along the brick-mortar interface [63]. This conclusion is in line with the recommendations of Eurocode 6 [21], which gives an indication of cohesion based on unit types, the compressive strength of the mortar, and joint thickness. Among the researchers [20,62], found a strong relationship, in which the cohesion of clay brick masonry was found respectively to be approximately 0.0471 and 0.27 times the mortar compressive strength,

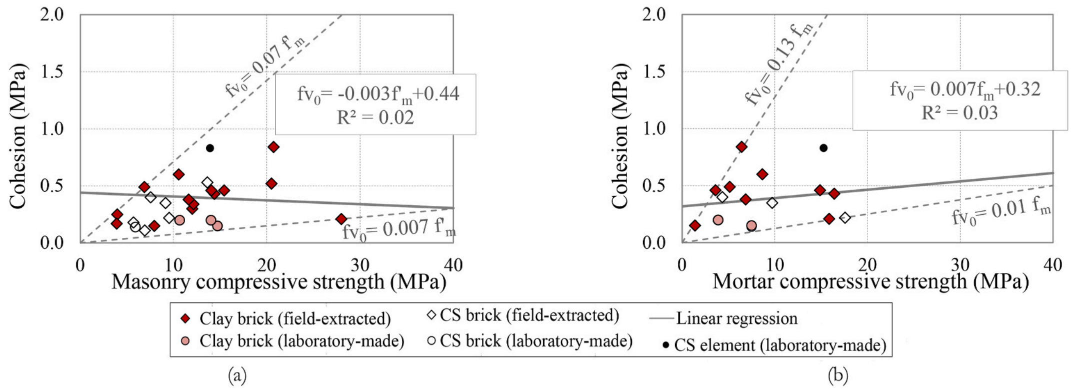

Fig. 9. Correlation between cohesion and: (a) masonry compressive strength; (b) mortar compressive strength.

Table 8
Ratio between cohesion, f_{v0}, and compressive strength of masonry, f'_m, and compressive strength of mortar, f_m. Correlation of determination in parentheses.

Reference	Masonry type	f_{v0}/f'_m	f_{v0}/f_m
[16]	Clay and CS brick masonry	0.008–0.096	0.023–0.135
[17]	Clay and CS brick masonry	–	0.043 (0.34)
[20]	Clay brick masonry	0.032 (−0.15)	0.047 (0.83)
[34]	Typical South African	–	0.350 (0.30)
[42]	Clay brick masonry	–	0.060–0.175
[62]	Clay masonry	–	0.27 (0.86)
This work	Clay brick masonry	0.007–0.071(0.09)	0.013–0.131(0.02)
	CS brick masonry	0.034 (0.60)	0.013–0.092 (0.16)
	CS element masonry	0.060 (–)	0.054 (–)
	All masonry types	0.008–0.071 (0.02)	0.013–0.131 (0.03)

see Table 8. Using the extensive experimental results from laboratory-made clay brick masonry, CS brick and block masonry reported by Ref. [17]; a similar relationship with a low correlation of determination was also found.

A correlation between the values of cohesion and uniaxial tensile strength might be expected, as both parameters depend on brick-mortar interface properties. For both brittle and quasi-brittle materials, the stress corresponding to the onset of cracking under bending load can be considered as uniaxial tensile strength. Although we did not perform a direct tensile test in this research, uniaxial tensile strength was indirectly evaluated from the bending tests as the stress at which the curve began to 10% deviate from its initial slope. Therefore, insight into the uniaxial tensile strength can be indirectly derived from the bending tests. By giving the ratio between the flexural strength and the uniaxial tensile strength, this study responds to the major demand in practice and research (e.g., see Refs. [17,64]).

Fig. 10a shows the relationship between derived tensile strength and flexural strength of wallets tested under vertical out-of-plane bending. In this study, the ratio of 0.78 was found between the derived tensile strength and the vertical flexural strength is in agreement with the ratio of 0.80 found by Ref. [17] as direct tensile tests and vertical out-of-plane bending tests were performed. Nevertheless, researchers such as [65,66] indicated a lower ratio of 0.33, meaning that there is a factor of three between tensile and flexural strength.

Fig. 10b shows the ratio between cohesion and tensile strength derived using the values of bond strength. To augment the database, the values of the tensile strength were indirectly evaluated using the relationships established earlier: 1) a one-to-one correspondence exists between the bond strength and vertical flexural strength of wallets obtained from vertical out-of-plane bending tests; 2) there is a factor of 0.78 between tensile strength and vertical flexural strength. As evident in Fig. 10b, no linear relationship was found between cohesion and derived tensile strength. A wide range of ratios was obtained varying from 0.44 to 3.85. These results seems to be consistent with those of [17]; who found a wide range varying between 1.3 and 7.5. Nevertheless instead of a regression analysis, he reported an average ratio of 2, with a coefficient of variation of 0.55. Taking a similar approach, we found a ratio of 2.18 with a coefficient of variation of 0.66.

3.9. Tensile fracture energy of mortar, units, and Mode-I fracture energy

The brittle nature of masonry and its constituents often hinders a full appreciation of the post-peak response, and thus the ability to quantify the fracture energy. Accordingly, to date, only a few studies

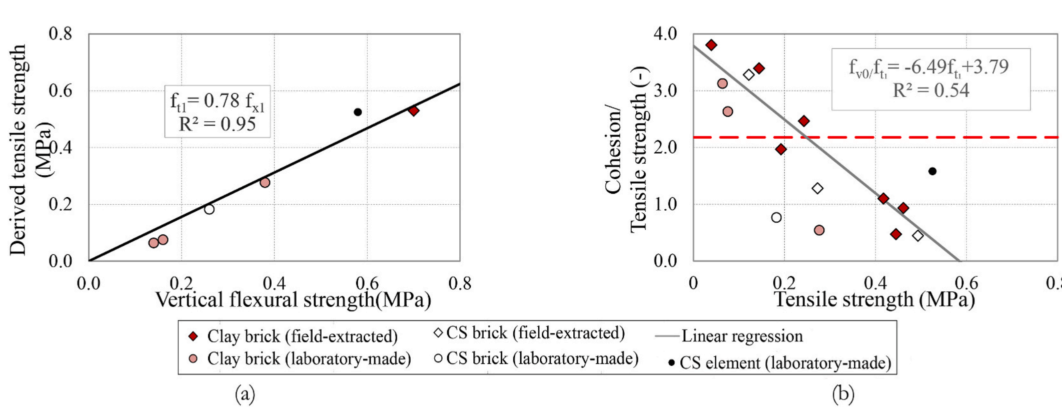

Fig. 10. (a) Correlation between flexural strength and derived uniaxial tensile strength under vertical out-of-plane bending load; (b) correlation between cohesion and derived tensile strength.

Table 9
Ratio between unit tensile fracture energy, $G_{f\text{-}tb}$, and tensile strength of unit, f_{tb}, and Mode-I fracture energy, $G_{f\text{-}I}$, and tensile strength, f_t. Correlation of determination in parenthesis.

Reference	Masonry type	$G_{f\text{-}tb}/f_{tb}$	$G_{f\text{-}I}/f_t$
[17]	Clay and CS brick	0.038 (0.51)	0.016 (0.35)
[44]	Clay brick	0.018 (–)	–
[67]	perforated clay brick	0.038	
[34]	Typical South African	0.013–0.071	
[68],*	Clay brick	–	0.029 (–)
	CS brick		0.052–0.064
This work**	Clay brick	–	0.031 (–)

* Values are obtained from bond wrench test.
** Values are obtained from vertical out-of-plane bending tests.

experimentally characterised the fracture energy of mortar, unit, and masonry under tensile loading. A summary of the available literature data is presented in Table 9.

So far there has been little discussion on the fracture energy of mortar under tensile load. In a recent study [69], established a relationship between mortar tensile strength, f_{tm}, and the fracture energy of mortar, $G_{f\text{-}tm}$, as follows:

$$G_{f-tm} = 100(f_{tm})^{0.8} \tag{4}$$

Moreover, in the absence of experimental results, several researchers, such as [70,71]; relied on the recommendation of Model Code 90 for concrete, whereby the tensile fracture energy of mortar.

$G_{f\text{-}tm}$, can be found as a function of mortar compressive strength, f_m, as follows:

$$G_{f-tm} = 0.025\left(f_m/10\right)^{0.7} \tag{5}$$

From the linear regression analysis of the experimental results presented by Ref. [17]; the tensile fracture energy of the clay and CS bricks can be approximated as 0.038 times the unit tensile strength. For one unit type, namely multi-perforated clay brick [67], found a ratio in line with the findings of [17]. However, this ratio is almost two times higher than that of [44]; which was found from tests on three types of clay bricks. For the typical South African units [34], found a ratio ranging widely from 0.013 to 0.071. As with mortar, in the absence of experimental results, the tensile fracture energy of brick is estimated in the literature using the expression from Model Code 90, Eq. (5).

Using the data reported by Ref. [17] obtained from uniaxial tests on 17 different masonry types, a ratio of 0.016 between the mode-I fracture energy and the tensile strength of masonry was found, though the correlation of determination was not strong (R^2 =0.35). In this research, we did not perform uniaxial tensile tests, however the bending properties obtained from the vertical out-of-plane bending tests can give indication on the tensile properties of masonry. To this end, Table 9 gives the ratio between the fracture energy and flexural strength of wallets under vertical out-of-plane bending tests. Though based on a limited amount of data, an average ratio of 0.021 was found, which accords with the findings of [17]. In a separate study on masonry built using the same materials as adopted in this study [68], managed to record the softening response of CS brick masonry and solid clay brick masonry couplets using a bond wrench test. As a result, Table 9 reports the ratio of fracture energy to the bond strength of couplets tested at 28 days. As seen in the table, the ratio of 0.031 found for clay brick masonry matched with our findings from the bending test. However, the ratio found for CS brick masonry is much higher as compared to clay brick masonry.

3.10. Shear fracture energy

Although fracture energy is commonly acknowledged as a size-independent property, in this study, as in previous studies (e.g. Refs. [17,72], a clear dependency of the mode-II fracture energy on pre-compression levels was observed. In this study, the shear-sliding deformations were systematically recorded only for three masonry types replicated in the laboratory. A linear relationship was established between mode-II fracture energy and pre-compressive stress of these three masonry types. As listed in Table 10, CS brick masonry and solid clay brick masonry showed an increasing trend between mode-II fracture energy and pre-compressive load, while mode-II fracture energy in MAT-2 perforated clay brick masonry decreased with an increase in the pre-compressive stress. This can be explained by a sudden reduction in the shear stress upon reaching the peak load. Accordingly, it can be concluded that mode-II fracture energy is affected not only by the pre-compressive stress, but also by the unit type.

Table 10
Mode-II fracture energy as a function of pre-compressive stress.

Reference	Masonry type	Expression
[17]	Lab-made CS brick masonry (lower limit)	$G_{f-II} = 0.02f_p + 0.005$
	Lab-made CS brick masonry (upper limit)	$G_{f-II} = 0.04f_p + 0.01$
	Lab-made clay brick masonry (lower limit)	$G_{f-II} = 0.02f_p + 0.005$
	Lab-made clay brick masonry (upper limit)	$G_{f-II} = 0.13f_p + 0.06$
This research	Lab-made CS brick masonry	$G_{f-II} = -0.01f_p + 0.02$
	Lab-made perforated clay brick masonry	$G_{f-II} = -0.09f_p + 0.17$
	Lab-made solid clay brick masonry	$G_{f-II} = 0.53f_p - 0.04$

Although a large body of literature exists regarding the shear properties of masonry, the current state of knowledge on mode-II fracture energy mainly relies on the experimental studies conducted by Ref. [17]. Table 10 lists the expressions established in this study and the ones found by Ref. [17] for CS brick masonry and clay brick masonry. Generally, in this study we found higher values of mode-II fracture energy than did [17]. Such a difference can be attributed to the use of different testing methods and specimen geometry. In this study, we adopted triplet specimens tested under shear-compression loading accordingly to Ref. [73]; while [17] used couplet specimens and an ad-hoc set up, aiming for a homogeneous shear distribution. As a coarse estimate, the mode-II fracture energy is often estimated to be ten times than that of Mode-I fracture energy [34,74]. However [71], assumed that the mode-II fracture energy can be estimated as 1/10 of cohesion. Assuming that mode-II fracture is evaluated at zero pre-compressive stress, neither approach suggested in the literature was able to provide an acceptable estimation of mode-II fracture energy for the analysed masonry types. To draw more precise conclusions regarding mode-II fracture energy and its influencing parameters, additional experimental studies are suggested.

3.11. Orthotropic behaviour of masonry under compression and bending loads

Masonry is treated as an orthotropic material, meaning that it exhibits distinct directional properties due to the bond stacking pattern and different arrangements of head joints and bed joints [75]. Accordingly, the influence of the bed joint orientation with respect to the principal stress needs to be considered. Under compression loading, the stiffness, strength and softening response of masonry could change depending on the loading direction. The same holds for in-plane tensile loading and in-plane bending, where either a line crack in bed joints, a stepped crack through bed joints and head joints, or a line crack through head joints and bricks may emerge. Finally, for out-of-plane bending load, the orthotropic behaviour of masonry is also essential, as bed joints act as a plane of weakness, and stepped cracks or line cracks may again emerge as distinct failure modes. Experimental and numerical attempts have been made in the literature to address the orthotropic behaviour of masonry by introducing a failure surface [76]. proposed a composite

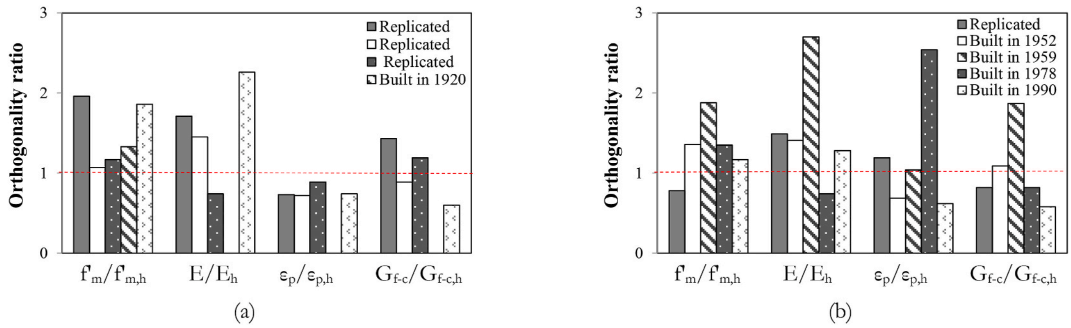

Fig. 11. Orthotropic behaviour under compression loading for compressive strength, $f'_m/f'_{m,h}$, Young's modulus, E/E_h, strain at peak, $\varepsilon_p/\varepsilon_{p,h}$, and compressive fracture energy, $G_{f\text{-}c}/G_{f\text{-}c,h}$: (a) clay brick masonry types; (b) CS brick masonry types.

Table 11
Mean values of orthotropic ratio under compressive loads. Number of masonry objects are in parentheses.

Masonry type	$f'_{m,h}/f'_m$	E_{3h}/E_3	$\varepsilon_{p,h}/\varepsilon_p$	$G_{f\text{-}c,h}/G_{f\text{-}c}$
Clay brick masonry	0.68 (5)	0.65 (4)	1.30 (4)	0.97 (4)
CS brick masonry	0.76 (5)	0.66 (5)	0.82 (5)	0.97 (4)
CS element masonry	0.69 (1)	0.69 (1)	0.81 (1)	–

Table 12
Orthotropic ratio under out-of-plane bending loads. Number of masonry objects are in parentheses.

Masonry type	f_{x2}/f_{x1}	E_{fx2}/E_{fx1}	f_{t2}/f_{t1}	G_{fx2}/G_{fx1}
Clay brick masonry	3.14 (5)	1.43 (4)	2.99 (4)	6.11 (3)
CS brick masonry	3.19 (2)	0.82 (1)	1.59 (1)	–
CS element masonry	1.26 (1)	0.69 (1)	0.82 (1)	1.87 (1)

yield criterion, in which the strength and the hardening/softening behaviour differed along each material axis. It is worth mentioning that the bending properties are not always directly implemented in assessment methods; however, they are often used to indirectly provide insights into the uniaxial tensile strength along with the softening parameters.

The orthotropic behaviour of masonry under compression loading is certainly not limited to strength, $f'_m/f'_{m,h}$, but can be extended to other properties such as stiffness, E/E_h, strain corresponding to the peak stress, $\varepsilon_p/\varepsilon_{p,h}$, and fracture energy, $G_{f\text{-}c}/G_{f\text{-}c,h}$. The ratios between the compression properties of wallets under vertical and horizontal loading for the clay and CS brick masonry are shown in Fig. 11a and Fig. 11b, respectively. Lower strength and stiffness can be expected under horizontal compression loading, since failure generally occurred by debonding of the bed joint interfaces rather than splitting of the bricks. In addition, under horizontal loading, the head joints are compressed, and these are often not adequately filled with mortar and considered to be of a poorer quality. As a result, under horizontal action, the Young's modulus is expected to be lower and the peak strain higher. In addition, more energy is expected to be consumed under horizontal loading, as bricks form a series of columns that can sustain further load [77]. However, the findings from tests on different masonry types showed that the orthotropic behaviour of masonry is not as straightforward as assumed, and the differences between the elastic properties of masonry constituents and unit types can lead to completely different behaviour. The average values of the orthotropic ratio under compression loading are listed in Table 11. Irrespective of the masonry type, the horizontal compressive strength and Young's modulus can be approximated to be 30% lower than the corresponding properties in the vertical direction. In line with the reduction of Young's modulus, the peak strain of the clay wallets can be estimated to be 30% higher than the peak strain in the vertical direction. However, the peak strain of the CS brick as well as the CS element masonry in the horizontal direction is found to be 20% lower than the corresponding values obtained in the vertical direction. Regarding the compressive fracture energy, no significant difference between horizontal and vertical direction was noticed; thus the orthotropic ratio was 1.

The ratios between the bending properties of wallets under vertical and horizontal loading for the clay and CS brick masonry are shown in Fig. 12a and Fig. 12b, respectively. The average values of the orthotropic ratio under bending loading are listed in Table 12. It is worth mentioning that Eurocode 6 [21] also provided insight into the characteristic flexural strength of different masonry types. Accordingly, it implicitly indicates a ratio of 4 between the horizontal and vertical

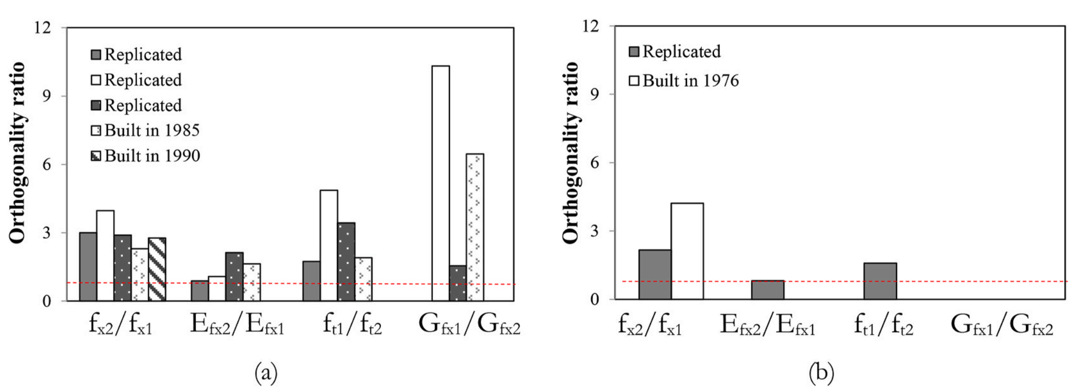

Fig. 12. Orthotropic behaviour under out-of-plane bending loading for flexural strength, f_{x2}/f_{x1}, Young's modulus, E_{fx2}/E_{fx1}, derived tensile strength, f_{t1}/f_{t2}, and bending fracture energy, G_{fx1}/G_{fx2}: (a) clay brick masonry types; (b) CS brick masonry types.

flexural strength of brick masonry for both clay and CS brick wallets, while a ratio of 2 is suggested for CS element masonry with thin layer joints. In this study, the ratio between the horizontal and vertical flexural strength of masonry with general-purpose mortar, i.e. clay and CS brick masonry, and CS element masonry with thin layer joints was found to be 3.2 and 1.3, respectively. These ratios are slightly lower than the ones recommended by Eurocode 6 [21]. Regarding the Young's modulus, clay brick masonry showed a higher stiffness under horizontal bending than under vertical bending, while for CS brick and CS element masonry an inverse trend was found. Regarding the derived values of tensile strength, the found orthotropic ratio was lower as compared to the values of flexural strength. Regarding the fracture energy, orthotropic ratios of 6 and 2 were found, respectively, for clay brick masonry and the element masonry. Note that the post-peak softening branch was captured only for a limited number of specimens. Accordingly, further tests are suggested to ensure the repeatability of the obtained ratios.

4. Conclusions

A complete picture of masonry characteristics, accounting for its full nonlinear response, has long been of scientific research interest worldwide, and it has become a necessity for the Netherlands in recent years. The absence of well-defined material parameters brings a set of tacit assumptions into the modelling process, thus reducing confidence in the reliability of the structural analysis. Hence, the more rigorously the input parameters can be determined, the more they can engender confidence in the reliability of the prediction models. This calls for an interdisciplinary approach, whereby experimental research is focused on meeting the demands of model developers. As a result, extensive laboratory testing and in-situ testing campaigns are needed to provide a basis for the validation and calibration of the various models to be used in deterministic or probabilistic settings. To minimise the extent of damage to existing masonry structures, semi-invasive testing methods which induce minor and easy-to-repair damage to the walls are gaining more grounds, such as laboratory tests on drilled small-diameter cores as well as in-situ flat-jack based testing methods (i.e. double flat-jack and shove tests). Through a comparative study in the past, the authors investigated the suitability of both testing methods to characterise material properties of typical Dutch brick masonry structures (e.g., see Refs. [78–81]. It was concluded that the accuracy of the strength and stiffness obtained from the flat-jack based testing methods is of concern and further studies are required to understand the effect of boundary conditions on toughness properties obtained from the core testing methods. As a result, at this moment, insight into the toughness and the orthotropic behaviour can be gained only through laboratory test on medium-sized specimen, which is not always practical.

Aiming to reduce the burden associated with performing complex experimental studies required to gain insights into strength, stiffness, and toughness, this paper explored the statistical relationships between different material properties of typical Dutch masonry dwellings built between 1912 and 2010. This is mainly achieved through the rich database established from performing compression, bending, and shear tests on laboratory-made and field-extracted specimens, mainly single-wythe brick masonry. To predict the relationship between two selected properties, linear regression analysis was conducted; the accuracy of the relationships was quantified by the values of correlation of determination (R^2). Strong relationships were found between the values of mortar compressive strength and mortar flexural strength, vertical flexural strength and bond strength, mortar compressive strength and bond strength, and vertical flexural strength and derived tensile strength. However, additional tests are of value, particularly to augment the database for mode-I fracture energy and mode-II fracture energy.

Taking advantage of the correlations established in this paper, Table 13 presents recommendations to define input parameters for structural analysis by performing a limited number of tests and minimising the damage caused due to testing or sampling. Accordingly, first,

Table 13
Recommendations to define the mean values of input parameters for structural analysis based on limited tests and the presented correlation study. These recommendations have been validated mainly for typical single-wythe Dutch masonry.

Properties	Sym.	Unit	Recommendation	
Masonry properties				
Vertical compressive strength	f'_m	MPa	Direct tests or indirectly derived as recommended in Eurocode 6 using compressive strength of brick and mortar.	
Vertical Young's modulus	E_3	MPa	$E_3 = (500 - 700)f'_m$	Masonry with conventional joint & Masonry with thin joint
Horizontal compressive strength	$f'_{m,h}$	MPa	$f'_{m,h} = (0.70 - 0.80)f'_m$	Masonry with conventional joint & Masonry with thin joint
Horizontal Young's modulus	$E_{3,h}$	MPa	$E_{3,h} = 0.70E_3$	Masonry with conventional joint & Masonry with thin joint
Vertical flexural strength	f_{x1}	MPa	$f_{x1} = f_w$	Masonry with conventional joint & Masonry with thin joint
Horizontal flexural strength	f_{x2}	MPa	$f_{x2} = 3f_w$	Masonry with conventional joint
			$f_{x2} = 1.3f_w$	Masonry with thin joint
Tensile strength	f_{t1}	MPa	$f_{t1} = 0.8f_w$	Masonry with conventional joint & Masonry with thin joint
Fracture energy in vertical compression	$G_{f\text{-}c}$	N/mm	$G_{f-c} = (0.88 - 5.3)f'_m$	Masonry with conventional joint
Fracture energy in horizontal compression	$G_{f\text{-}c,h}$	N/mm	$G_{f-c,h} = G_{f-c}$	Masonry with conventional joint
Mortar and brick properties				
Mortar compressive strength	f_m	MPa	$f_m = f_w/0.036$	
Mortar Young's modulus[1]	E_{3m}	MPa	$E_{3m} = (200 - 240)f_m$	
Mortar tensile strength[2]	f_{tm}	MPa	$f_{tm} = (0.15 - 0.32)f_m$	
Mortar fracture energy in tension[3]	$G_{f\text{-}tm}$	N/mm	$G_{f-tm} = 0.025(f_m/10)^{0.7}$	
Brick compressive strength	f_b	MPa	Direct test	
Brick Young's modulus[4]	E_{3b}	MPa	$E_{3b} = (300 - 430)f_b$	
Brick tensile strength[5]	f_{tb}	MPa	$f_{tb} = (0.04 - 0.07)f_b$	
Brick fracture energy in tension[6]	$G_{f\text{-}tb}$	N/mm	$G_{f-II} = 10G_{f-I}$	
Interface properties				
Bond strength	f_w	MPa	Direct test	
Initial shear strength/cohesion	f_{v0}	MPa	Direct test	
Initial friction coefficient	μ	-	Direct test	
Fracture energy in tension[6]	$G_{f\text{-}I}$	N/mm	$G_{f-I} = 0.16f_{t1}$	
Fracture energy in shear[7]	$G_{f\text{-}II}$	N/mm	$G_{f-II} = 10G_{f-I}$	

[1] Based on studies from Refs. [18,22].
[2] Based on studies from Refs. [16,42]. Note that in the lack of experimental results the tensile strength of mortar assumed to be the same as its flexural strength.
[3] Expression is extracted from Model Code 90 for concrete.

[4] Based on studies from Refs. [16,22]; and [18].
[5] Based on studies from Ref. [16].
[6] 'Based on study from Ref. [17].
[7] Based on studies from Refs. [34,74].

by performing a limited number of semi-invasive tests the following material properties can be directly determined: (i) vertical compressive strength and Young's modulus of masonry by compressing small-diameter cores or using in-situ double flat-jack tests; (ii) shear properties of brick-mortar interface in terms of cohesion and friction coefficient using shear-sliding tests on small-diameter cores or in-situ shove tests; (iii) bond strength using simple bond wrench set-up; (vi) compressive strength of bricks by compressing intact bricks that remain from bond wrench tests. Second, insights into the mortar properties, bending properties, tensile properties, toughness, and orthotropic behaviour can be indirectly gained using the expressions found in Section 3 or established in literature (as stated in footnote of Table 13). Note that the recommendations on the tensile properties are mainly extracted from the literature data, given that the tensile tests were not performed in this study. In view of the recommendations presented in Table 13, an acceptable level of knowledge on material properties with a distinct level of refinement can be obtained by performing a limited number of tests, thus minimising the extent of invasiveness and saving time and cost.

CRediT authorship contribution statement

Samira Jafari: Conceptualization, Methodology, Validation, Data curation, Writing - original draft. Jan, G. Rots: Conceptualization, Writing - review & editing, Supervision, Funding acquisition. Rita Esposito: Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Data for reference

The experimental results of the presented tests are available via the 4TU.ResearchData repository at https://doi.org/10.4121/15131979. The data are distribute under the license type CC BY.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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