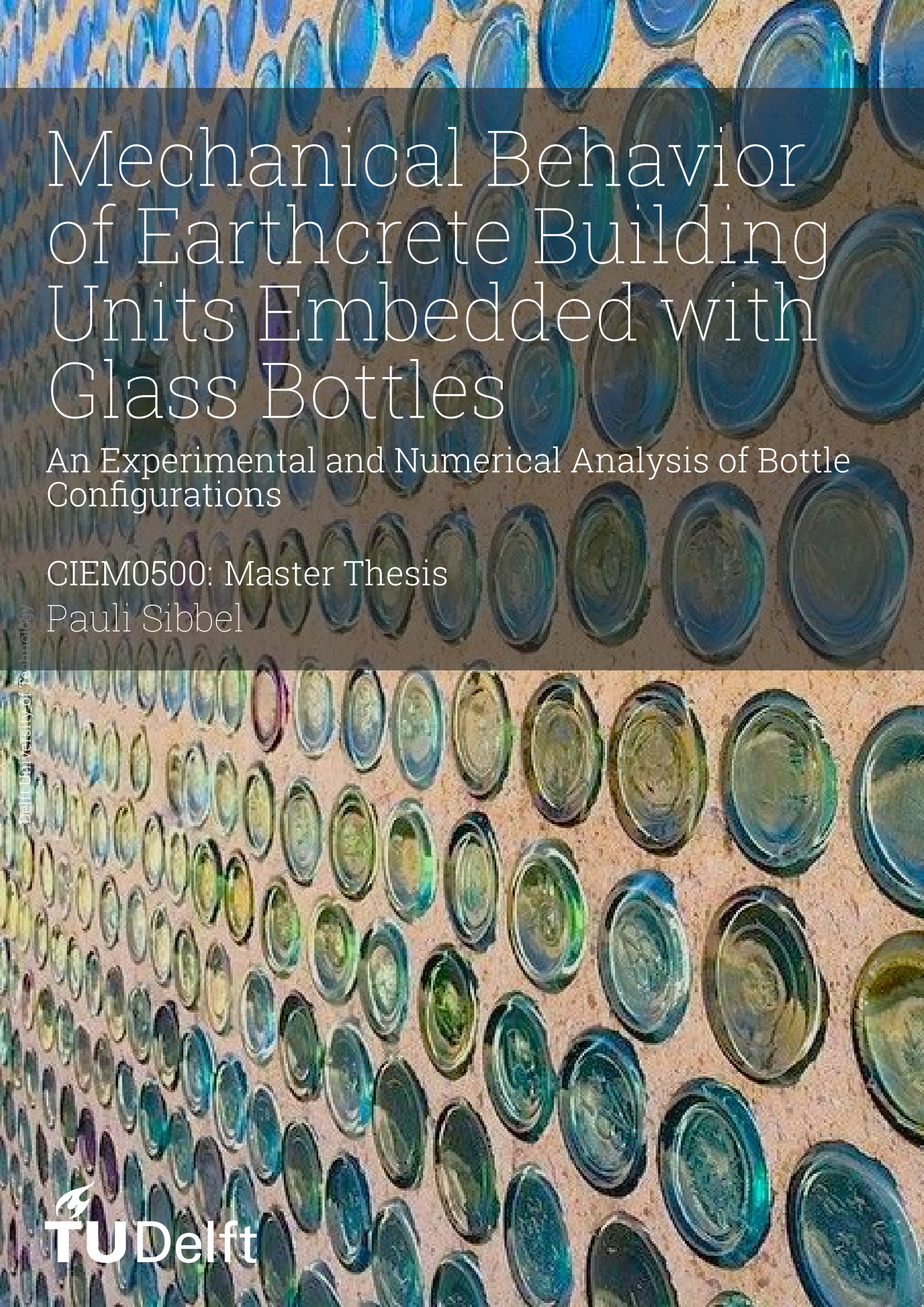




Mechanical Behavior of Earthcrete Building Units Embedded with Glass Bottles

An Experimental and Numerical Analysis of Bottle
Configurations

CIEM0500: Master Thesis

Pauli Sibbel

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by

Pauli Sibbel

Student name	Student number
Pauli Sibbel	4701798

Author: P. (Pauli) Sibbel
Master Student Building Engineering, Structural Design - TU Delft

Chairman: Prof.dr.ir. L.J. Sluys
Supervisors: Ir. H. (Hoessein) Alkisaie
Dr. J. (Jagoda) Cupač
Dr.ir. A.T. (Abraham) Gebremariam

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Faculty: Faculty of Civil Engineering and Geosciences, Delft

Preface

*Pauli Sibbel
Delft, August 2026*

Herewith the thesis 'Mechanical Behavior of Earthcrete Building Units Embedded with Glass Bottles', a study on the repurposing of waste glass embedded in earthcrete mortar. This thesis is written for the completion of the master's Civil Engineering, track Building Engineering at the TU Delft. The final project was carried out from June 2025 until the oral defense on August 2026, at Delft University of Technology, with the experimental campaign performed in the Stevin Laboratory.

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Abstract

Glass is endlessly recyclable, yet only a fraction of container glass is recycled globally, while countries such as Brazil simultaneously face a severe shortage of affordable housing. In response, low-income communities have begun embedding used glass bottles in earthen mortars to construct walls. However, scientific investigation of glass bottles as structural components in earthcrete blocks is virtually absent from the literature. This thesis investigates the influence of different bottle configurations on the mechanical behavior of earthcrete building units embedded with long-neck beer bottles, using a combined numerical and experimental approach. Finite element models were developed in Abaqus using the Concrete Damage Plasticity model, calibrated on experimental data from earlier research on single-bottle blocks. A parametric study of cubic blocks (240 mm) was performed in which the number of vertically oriented bottles (0–9) and the earthcrete cover (2–6 cm) were varied. Based on these simulations, three configurations were fabricated and tested under uniaxial compression. The experiments proved highly repeatable: the plain block reached a mean capacity of 401 kN, whereas the four- and five-bottle blocks reached 330 kN and 349 kN respectively, corresponding to a capacity reduction of 13–18% and a distinctly more brittle post-peak response. The calibrated numerical model over-predicted the experimental capacities by 42–125% and incorrectly predicted that capacity increases with bottle count. Recalibration improved the agreement but remains a fit rather than a validation. A Eurocode 6 case study demonstrates that a two- to three-storey residential building on bottle-embedded walls satisfies the ultimate limit state verification with substantial margin. It is concluded that embedded glass bottles act not as reinforcement but as functional voids: for a modest loss of compressive capacity, they reduce material use and divert waste glass from disposal, making their value primarily economic and environmental rather than structural.

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Nomenclature

Abbreviations

Abbreviation	Definition
AGR	American Glass Research
CDP	Concrete Damage Plasticity (material model)
CGBEB	Cubic Glass Bottle Earthcrete Block
CSC	Concrete Smeared Cracking (material model)
C3D4	4-node linear (first-order) tetrahedral solid element (Abaqus)
C3D10(M)	10-node quadratic (modified) tetrahedral solid element (Abaqus)
EN	European Norm (Eurocode)
FEM	Finite Element Method
GBEB	Glass Bottle Earth Brick
GFI	Mode I fracture energy input parameter (Abaqus)
MRQ	Main Research Question
PCE	Polycarboxylate Ether (superplasticiser)
RC	Reinforced Concrete
SQ	Sub-Question
U.C.	Unity Check
ULS	Ultimate Limit State

Symbols

Symbol	Definition	Unit
A	Cross-sectional area	[mm ²]
d_c	Compressive damage variable	[-]
d_t	Tensile damage variable	[-]
E	Young's modulus	[MPa]
e	Load eccentricity	[mm]
F	Force	[N]
f_{b0}/f_{c0}	Ratio of biaxial to uniaxial compressive strength (CDP)	[-]
f_c	Compressive strength	[MPa]
f_d	Design compressive strength of masonry	[MPa]
f_k	Characteristic compressive strength	[MPa]
f_{mean}	Mean compressive strength	[MPa]
f_t	Tensile strength	[MPa]
G_f	Fracture energy	[N/mm]
G_k	Characteristic permanent load	[kN/m]
g	Permanent area load	[kN/m ²]
h_{ef}	Effective wall height	[mm]
K	Shape factor of the yield surface (CDP)	[-]
N_{Ed}	Design axial load per unit length of wall	[kN/m]
N_{Rd}	Design axial resistance per unit length of wall	[kN/m]
Q_k	Characteristic variable load	[kN/m]
q	Variable area load	[kN/m ²]
R_{outer}	Outer radius of the bottle body	[mm]
t	Wall thickness	[mm]
u	Displacement	[mm]
V	Velocity	[m/s]
Δt	(Stable) time increment	[s]
β	Friction angle	[°]
γ	Unit weight	[kN/m ³]
γ_M	Partial material factor	[-]
ε	Strain	[-]
ϵ	Flow potential eccentricity (CDP)	[-]
ε_{cr}	Cracking strain	[-]
ε_{in}	Inelastic strain	[-]
ε_{pl}	Plastic strain	[-]
μ	Viscosity parameter (CDP)	[-]
ν	Poisson's ratio	[-]
ρ	Density	[kg/m ³]
σ	Stress	[MPa]
σ_c	Compressive stress	[MPa]
σ_{Ed}	Design compressive stress in the wall	[MPa]
σ_t	Tensile stress	[MPa]
Φ	Capacity reduction factor for slenderness and eccentricity	[-]
ψ	Dilation angle (CDP)	[°]
ψ_0	Load combination factor (EN 1990)	[-]

1

Introduction

Glass is widely regarded as a material that can be endlessly recycled within a closed loop without loss of quality. Despite this potential, only an estimated 21% of global glass production is currently recycled. Container glass achieves the highest recycling rate of all glass categories, yet even this reaches only 32% globally [8].

Recycling rates of glass containers vary significantly across countries and regions, influenced by factors such as consumer awareness, geographic scale, regional economic disparities, and the availability of recycling infrastructure [8]. Beyond recycling, there is also the option of reusing glass containers. However, returning used bottles to producers remains challenging in some regions due to inadequate collection infrastructure [17].

For example, Brazilian glass production and recycling data reveal significant gaps in material recovery. According to the Brazilian Association of Glass Industries (Abividro), national production reaches 8.6 billion glass units annually, yet only 300,000 tons are recycled [7]. The beer bottle sector exemplifies this inefficiency, with approximately 630,000 tons produced yearly and merely 50% recycling rates. Glass that is not recycled or reused gets incinerated or ends up in landfills, where it accumulates in the environment. Because glass is a non-biodegradable material, it can remain in the environment for millions of years without decomposing, contributing to long-term accumulation of waste.

Brazil simultaneously faces a severe housing crisis, with a rising number of people experiencing homelessness and a substantial share of the population living in inadequate housing. The housing deficit is more pronounced in Rio de Janeiro, where it is estimated that 20% of residents live in informal shanty towns, known as 'favelas' (Gual, 2023) [22].

In light of these challenges, an underutilized waste stream and an unmet demand for affordable housing, builders have begun repurposing used glass bottles as building materials, often combining them with traditional earthen techniques. The abundance of low-cost labor and locally available materials facilitates affordable housing construction while simultaneously mitigating environmental pollution. Similarly, countries like Nigeria, India, Bangladesh, and Panama have seen a significant surge in the use of plastic bottles in combination with earth-based mortars for construction of affordable housing [37][30]. Urban junk such as plastic bottles can in this way be upcycled to replace conventional material such as brick in the construction of housing. Despite the fact that a considerable amount of research has been undertaken on the use of plastic bottles as a construction element, comparatively little research has been conducted on glass bottles.

Scientific investigation of glass bottles as structural components in earthcrete blocks remains virtually absent from the literature. Furthermore, the configuration of the glass bottles is expected to have an influence on the properties of embedded earthcrete blocks [5].

This thesis aims to address this research gap by examining the mechanical behavior of earthcrete units embedded with glass container bottles in different configurations.

The term configuration describes the organization of the bottles within a wall unit, encompassing their orientation, spatial arrangement and quantity. Orientation refers to the directional alignment of the bottles (horizontal or vertical). Spatial arrangement refers to the distribution or "collective pattern" created by the bottles within the wall as well as the distance between adjacent bottles and proximity of the bottle's ends to the wall's outer surface.

1.1. Problem statement of this thesis

The lack of affordable housing opportunities and escalating prices of conventional building materials have left significant portions of the Brazilian population homeless or living in inadequate conditions. In response, low-income communities have developed novel construction techniques utilizing locally sourced materials, in particular earthcrete (a mixture of natural soil and cement) combined with recycled glass bottles to create structural wall elements.

Previous research has investigated the load bearing capacity of earthcrete blocks containing a single embedded glass bottle [5]. To improve the credibility and applicability of the concept, however, further investigation is needed into different bottle configurations, including variations in orientation, arrangement and quantity. In addition, there is a notable gap in the understanding of how the earth-based mortar and the glass container interact numerically to form a single composite unit.

This thesis therefore investigates the mechanical properties and structural behavior of glass-bottle embedded earthcrete blocks through a combined numerical and experimental approach. Different bottle configurations are analysed under controlled compressive loading using finite element modeling and laboratory testing. Through systematic comparison of these configurations, the research aims to understand what influence different bottle configurations have on the earthcrete units and, on that basis, to provide an indication for developing structural walls with embedded glass bottles.

1.2. Main research question and sub-questions

The following main research question is formulated as follows:

"What is the influence of different bottle configurations on the mechanical behavior of earthcrete wall elements embedded with longneck beer glass bottles?"

The main research question will be answered with the help of four sub-questions:

SQ1: *"What configurations of glass bottles have been used in existing case studies as load-bearing wall components, and which configurations (existing or other) are most relevant for this research?"*

SQ2: *"What are the key physical properties and mechanical behavior of the longneck beer glass bottle and the earthcrete mixture relevant for this research?"*

SQ3: *"How do different block configurations perform (maximum loads and failure behavior) under compressive loading, as evaluated through Finite Element Modeling (FEM) and experimental testing?"*

SQ4: *"Which bottle configurations offer the best trade-off between maximizing the number of embedded bottles and limiting the loss of load-bearing capacity and buildability of the wall element?"*

1.3. Methodology

This research follows a numerical–experimental–numerical workflow, inverting the conventional order in which experiments precede modeling. The starting point of this thesis involves analyzing existing

experimental data from compression tests on the individual constituents: single glass bottles (undamaged and abraded) and earthcrete specimens, both plain and with a single embedded bottle. In the first numerical phase, a finite element model of the single-bottle block (GBEB) is built in Abaqus using the concrete damage plasticity (CDP) formulation, and its damage parameters are calibrated iteratively against these tests. In the second numerical phase, the calibrated model is scaled to cubic multi-bottle blocks (CGBEBs), in which bottle count (B0–B9) and earthcrete cover (C2–C6) are varied to identify the most promising configurations. The best-performing configurations are then carried into the experimental phase, in which they are cast and tested under uniaxial compression (Chapter 9). In the final numerical phase, the models are recalibrated against the block-scale experimental results. The experimentally obtained strengths are subsequently applied to a wall-level design verification according to Eurocode 6 (Chapter 10).

1.4. Research Objective

The following main objectives will be addressed in this thesis:

- Explore the potential of Glass Bottle Earthcrete Brick (GBEB) as a building material.
- Design GBEB units with different configurations.
- Increase knowledge on the mechanical behavior of glass container bottles embedded in earthcrete blocks.
- Identify limitations of earthcrete blocks embedded with glass bottles and formulating recommendations for further research and improvement.
- Investigate if the research approach (numerical – experimental – numerical) is a valid design strategy for testing blocks with different configurations.

1.5. Report Outline

This thesis report is subdivided into five sections:

1. State of the Art (Chapters 2-4)
2. Numerical Investigations (Chapters 5-8)
3. Experimental Investigations (Chapter 9)
4. Final numerical calibration (Chapter 10)
5. Wall Design (Chapter 11)
6. Discussion, Conclusion and Recommendations (Chapters 12-13)

Table 1.1 presents the report structure and maps each section to its corresponding research questions (Q), where SQ denotes sub-questions and MRQ the main research question.

Table 1.1: Report structure and methodology.

Part	Methodology	Chapter contents	RQ
State of the Art	Literature review	2. Exploring bottle configurations through different case studies 3. Physical characteristics of the Long-neck Beer Bottle 4. Mechanical behavior of Longneck Beer Bottles and Earth Based Mortar	SQ1, SQ2
Numerical Investigations	Finite Element Analysis (Abaqus)	5. Theory behind CDP and Brittle Cracking models 6. FEM modeling of a single glass bottle 7. Numerical investigations of earthcrete blocks embedded with a glass bottle 8. Numerical analysis of different CG-BEB configurations	SQ3
Experimental Investigations	Compression testing (Stevin laboratory); AGR bottle tests	9. Compression testing of different configurations	SQ3
Final Numerical Calibration	Recalibration of the FE models against block-scale tests	10. Final numerical calibration	SQ3
Earthcrete Wall Design	Case study calculation (Eurocode 6)	11. Wall design	SQ3, SQ4
Discussion, Conclusion and Recommendations	Review of results	12. Thesis discussion and Conclusion 13. Research recommendations	MRQ

LITERATURE REVIEW

2

Exploring bottle configurations through different case studies

This chapter examines case studies where glass bottles are integrated into structural and non-structural walls, with particular focus on different bottle configurations including orientation of the bottles and spatial arrangement.

2.1. Temple Wat Pa Maha Chedi Kaew

The Buddhist temple Wat Pa Maha Chedi in Thailand represents a remarkable case study in sustainable architecture, featuring 20 structures built entirely from approximately 1.5 million reused glass bottles from beer brands such as Heineken and Singha. Local monks initiated the construction of the temple in response to the increasing accumulation of waste in nearby landfills. Unlike other study cases that typically employ either horizontal or vertical orientations, the temple's builders experimented with a wide range of configurations, including vertical, horizontal, diagonal, mirrored and checkered configurations (see figure 2.1) [46]. These bottles are positioned relatively close to each other with cement as the binding material. Unfortunately, on April 23, 2024, a portion of the complex collapsed under its own weight, caused by a lack of weight-bearing pillars at one side of the pagoda [44].

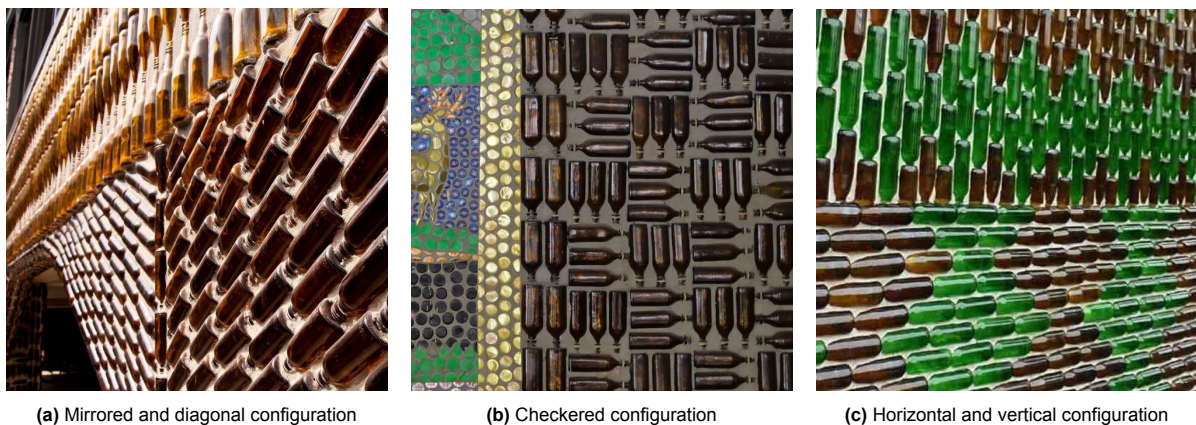


Figure 2.1: Bottle configurations in Temple Wat Pa Maha Chedi in Thailand

2.2. Beer bottle house in Tamil Nadu, India

Mr. Dilip Patel, an architectural graduate from the United Kingdom, constructed a residence known as the Beer Bottle House in the Indian state of Tamil Nadu. The property housing the beer bottle structure was found to be severely polluted by post-party bottle and plastic waste prior to its construction.

Observing the ongoing pollution of the environment, Patel initiated the coordination of cleanup initiatives and awareness programs. Inspired by online examples of bottle construction, he began collecting hundreds of discarded bottles, eventually sourcing 5,000 through local scrap dealers. Subsequently, the construction of the 3×4 m house could be initiated, using recycled glass bottles and locally sourced mortar.

The walls incorporate two layers of bottles arranged horizontally, with half of the bottles facing inward and half outward. The spaces between the bottles were filled with a mixture of cement and locally sourced red soil.

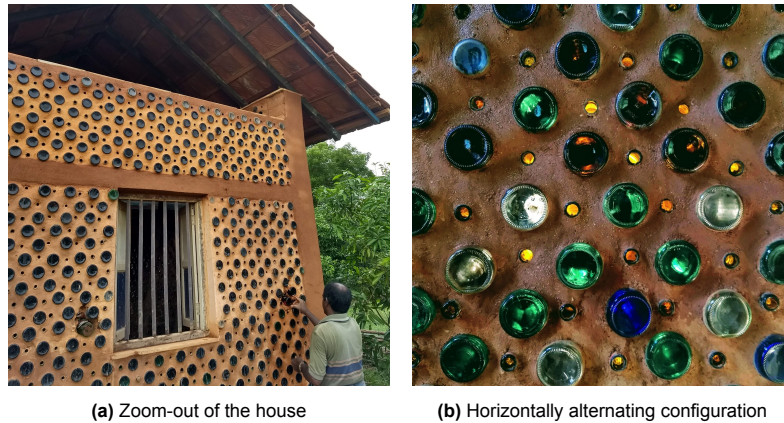


Figure 2.2: Beer Bottle House in Tamil Nadu, India

2.3. Glass Bottle House, Canada

Constructed by Edouard Arsenault in Wellington, Canada, this project utilized approximately 25,000 glass bottles, initially sourced from local waste sites and later supplemented by donations from community members and nearby bars and clubs in support of the initiative [27]. The whole project consists of 3 structures.

The bottles are sticking out slightly compared to the two previous study cases, as depicted in Figure 2.3. The glass bottles are mostly stacked on top of each other horizontally in a uniform way with a layer of cement to bind the bottles together.



Figure 2.3: Horizontal configuration

2.4. Other projects

Beyond the case studies mentioned above, numerous other projects also incorporate glass bottles as structural elements in walls. Most follow a standard configuration, with bottles laid horizontally and bonded together using mortar. These projects are typically single-story residential buildings.

Two other projects stand out for their unconventional designs and unique approaches:

- **Glass Bottle House (Florianopolis, Brazil):** This project breaks away from traditional layouts by using bottles of varying shapes and sizes in an irregular arrangement.
- **Blotto Grotto (Glass Bottle Dome, Pembrokeshire, UK):** Unlike typical bottle walls, this structure features two reinforced concrete arches that divide the dome into four sections. These sections were then filled with bottles arranged radially, their openings facing inward, both to prevent water ingress and to create a striking visual effect.



(a) Irregular configuration



(b) Radial configuration

Figure 2.4: Glass Bottle House (Florianopolis, Brazil) (left) and Blotto Grotto (Glass Bottle Dome, UK) (right)

2.5. Conclusion

Based on the findings presented in this chapter, it is evident that glass bottles have been implemented in a variety of configurations in real-world applications. While their arrangement varies from project to project, the most common, and likely most practical application is horizontal placement of the bottles in the walls. This is likely due to the ease of stacking given the uniform shape of the body of the bottle. In most of the case studies the openings of the bottles are facing inwards. This deliberate positioning helps prevent insect infestation and water ingress.

The identified configuration typologies include:

- Horizontal configuration
- Vertical configuration
- Diagonal configuration
- Radial configuration
- Alternating horizontal configuration
- Checkered configuration
- Mirrored configuration

Although precise measurements are unavailable, most projects appear to maintain a small gap (typically under 5 cm) between bottles to accommodate mortar placement. In some cases, the inter-bottle spacing is negligible due to the direct placement of the bottles side-by-side.

A diverse range of glass bottle configurations have been employed in practice. It is therefore relevant to investigate which glass bottle configurations are most favorable for the overall behavior of a wall consisting of earthcrete and embedded glass bottles.

Physical characteristics of the Longneck Beer Bottle

This chapter gives an overview of the characteristics of the glass bottle that will be used in this research: the 330 ml Long-neck Beer Bottle. These characteristics are important to discuss before any numerical simulations or experimental tests are performed.

3.1. Geometrical characteristics of glass bottles

Glass containers are available in a wide variety of shapes and forms. However, for the purposes of this thesis, the research will involve a single type of beer bottle: the 330ml Long-neck Beer Bottle. On average, an empty bottle of this type weighs approximately 300 grams, with a height of 238 mm. The additional geometrical characteristics can be found in table 3.1. A more elaborate overview of the bottle's geometrical characteristics can be found in annex A.

Table 3.1: Geometrical characteristics of long-neck beer bottles, 33 cl given by Brouwland

Dimension	Value	Unit
Height	238	mm
Outer diameter	61 ± 1.3	mm
Weight	Ca. 300	g
Content	33	cl

The bottle's structure can generally be divided into five distinct parts: Neck, Finish, Shoulder, Body and Heel [40].

3.1.1. Neck and finish

The finish is located at the top part of the bottle above the neck ring parting line. Beer bottles generally have a type of finish called crown finish. This is also the part on which the cap or closure is fastened to seal the bottle's contents. The crown finish has a slight extrusion at the top called "sealing surface" to allow the fastening of the seal. The neck is the region between the parting line of the finish and the shoulder region.

3.1.2. Shoulder

The shoulder is the region between the neck and the body of the bottle. The upper boundary of the shoulder is situated at the anticlastic principal curvature of the bottle and the lower boundary is located at the synclastic principal curvature, transitioning to a zero Gaussian curvature.

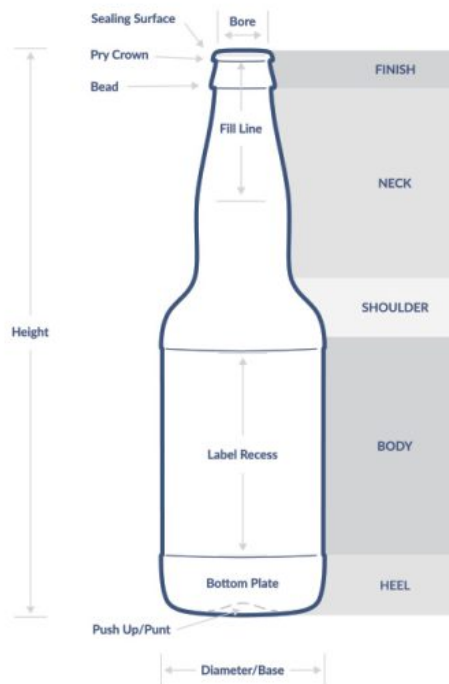


Figure 3.1: Long-neck beer bottle anatomy [45]

3.1.3. Body

The body is the largest part of the glass bottle and is situated between the shoulder and the base of the bottle. The body has a uniformly cylindrical shape where brand labels can be bonded to. Some beer bottles such as the 330 ml Heineken Star bottle contain small recessed label panels. These recesses serve several key purposes: provide additional protection to the applied paper labels, increase visual appeal and/or tactile feel of the container. However, these irregularities create localized stress concentrations when the bottle is axially loaded. Deeper recesses may lead to higher localized stresses, potentially affecting the bottle's overall strength [47].

3.1.4. Heel

The heel of a glass beer bottle is located at the bottom of the container, below the body. It contains the bearing surface of the bottle. The heel contains 'punt marks' to indicate the company that produced the bottle, the capacity, and type of machine used to manufacture it. The heel has a curved synclastic surface which creates an area with higher stiffness. The bearing surface of the bottle is the part that rests on the supporting surface and is the most likely to be damaged while handling.

3.2. Coatings

An important factor influencing the strength of glass containers is the degree of damage inflicted to the outer surface during the manufacturing procedure and subsequent handling, resulting in scratches, abrasions and/or flaws.

Surface defects in the glass significantly diminish the bottle's practical strength, reducing it to only a fraction of the theoretical strength of an undamaged surface [39]. Thus, it is important to protect the outer glass surface directly after the molding process, which is accomplished by surface treatments. Returnable containers are generally heavier than non-returnable containers to account for the progressive aggregation of abrasions on the glass with each trip back to the filling factory [14]. Both the refillable as well as the non-refillable bottles require coatings to strengthen the outer surface of the containers.

The coatings allow for increased handling speed during manufacturing and customer operations, such as inspection, packing, unpacking, cleaning, filling, labeling, and final packaging before distribution to consumers [26]. The first coating is applied directly after the bottle forming process, also referred to as the hot-end coating. After the glass comes out of the annealing lehr, the containers get a second coating called the cold-end coating [39].

During FEM modeling and experimental testing, the outer surface of the glass bottles will be in direct contact with the Earthcrete matrix. Therefore, it is important to understand which types of coatings are applied to the bottles as they will have an influence on the bonding strength between the earthcrete and the glass surface. This subchapter provides a literature review revolving around these aspects.

3.2.1. Hot-end coating

After the bottle forming process, the bottle is transferred from the IS machine to a conveyor belt, which transports it to the annealing furnace. Prior to entering the annealing lehr, each bottle receives a tin oxide (SnO_2) coating via chemical vapor deposition (CVD) at temperatures of about 550-600 °C. This process uses monobutyl tin trichloride (MBTC) or tin tetrachloride (SnCl_4) as precursor compounds, which decompose to form the adherent surface layer of SnO_2 . The hot-end coating serves as an adhesive layer (or bonding coat) for the subsequent cold-end coating.[36]. The coating has a thickness typically between 2 and 10 nm.

3.2.2. Cold-end coating

After the bottles come out of the annealing lehr, the glass containers are coated with an additional protective layer known as the cold-end coating. This coating is applied primarily to prevent damage to the outer surface caused by sliding contact during filling, transport and use. The cold-end coating consists of a non-toxic polymer film, typically containing either oleic acid or polyethylene blends, which provide good lubricity and abrasion resistance [39]. By reducing the contact friction between the bottles, the coating facilitates smoother handling on conveyor belts at the cold end, as well as in inspection machines and filling lines at the customer's facility [36]. The application process involves spraying the bottles with a concentrated polyethylene emulsion immediately after they leave the lehr. At temperatures of about 85-110°C, the water content evaporates, leaving behind a thin, durable polyethylene film over the existing hot-end coating. The film has a thickness ranging from 1 to 2 nm. Notwithstanding, the film should not influence the amount of torque required to remove the bottle top [39].

3.3. Knurls

Most glass containers feature knurls on their bearing surfaces. Knurls are typically designed in four configurations: bar, crescent, dot, and chain. Beverage bottles most often present bar or crescent knurls, whereas food jars have bar, crescent, or dot knurls. Chain knurls are occasionally applied to liquor and still wine bottles, but their usage is restricted due to the higher risk of micro-cracks formation during bottle manufacturing [16]. Dr. Wenke Hu, PhD, of American Glass Research (AGR) conducted a comprehensive investigation into stress distribution patterns and peak stress magnitudes in bearing surfaces under both internal pressure and impact loading conditions using finite element analysis (FEA) modeling [16]. The bottle model included 66 equidistant knurls on its bearing surface with a height of 0.43 mm. These features are typical for a 330ml bottle. Dr. Wenke Hu observed that all knurl configurations exhibited comparable stress behavior: reduced tensile stress at knurl tips but higher stress concentrations between knurls. Handling-induced damage to the bearing surface of the bottle usually stays confined to the tips of the knurls, where the stress indices are low. Thereby, breakage can typically be averted [16].

4

Mechanical behavior of Longneck Beer Bottles and Earth Based Mortar

In this research project, the type of bottle and the composition of the earth-based mortar remain constant. The primary variable under investigation is the configuration of glass bottles embedded within the mortar. To provide context, the individual strength of the long-neck beer bottles and the earth-based mortar will be discussed as well as other material properties. In addition, this chapter will present the structural performance of earth bricks embedded with a single glass bottle.

4.1. Material properties of soda-lime container glass

Container glass (such as bottles, jars and other packaging) is primarily made of soda-lime-silica glass, though with some compositional differences compared to flat glass. Long-neck Beer Bottles contain colorants and additives, added during manufacturing, which give them their characteristic green or amber tints. These include Iron Oxide (Fe_2O_3), Sulfur-carbon complexes ($S + C$) and Manganese Dioxide (MnO_2) [15]. These substances are incorporated to provide UV protection, blocking wavelengths that can degrade the bottle's contents. Additionally, alumina Al_2O_3 is added to increase the overall durability and enhance the bottle's impact resistance. The material properties of an abraded Longneck Beer Bottle with severe abrasions are presented in table 4.1.

Table 4.1: Material properties of an abraded longneck beer bottle (with severe abrasions) [24]

Material property	Value	Unit
Young's Modulus	69930 ^a	MPa
Poisson's Ratio	0.21 ^a	-
Shear Modulus	28780 ^a	MPa
Long-term characteristic tensile strength	11.7 ^b	MPa
Density	2465	kg/m ³

^a Data compiled by Ansys Granta, incorporating various sources including JAHM and MagWeb.

^b Data provided by AGR [24]

The characteristic tensile strength is a statistical measure used to define the strength of a material. It refers to the tensile strength value below which no more than 5% of test results are expected to fail. While the characteristic tensile strength of glass will provide a statistical probability of expected strength, it does not accommodate uncertainties associated with expected load duration or load conditions. In the Eurocode designated for glass, the design strength is derived by applying a modification factor (k_{mod}) to the characteristic strength, where k_{mod} incorporates time-dependent strength reduction under

sustained loading. The tensile design strength of glass depends thus on a number of factors, discussed in the following section.

4.1.1. Tensile design strength of glass

The tensile design strength of annealed glass, $f_{mt;u;d}$, is calculated according to NEN 2608:2014 [50] as follows:

$$f_{mt;u;d} = \frac{(k_a \times k_e \times k_{mod} \times k_{sp} \times f_{g;k})}{\gamma_{m;A}} \quad (4.1)$$

Where:

$f_{mt;u;d}$ is the design tensile strength of glass

k_a is the area factor

k_e is the edge factor

k_{mod} is the load duration factor

k_{sp} is the surface factor

$f_{g;k}$ is the characteristic bending strength (with $f_{g;k} = 45 \text{ N/mm}^2$)

$\gamma_{m;A}$ is the material factor for float glass (with a value of 1.6)

The equation contains a characteristic value and factors relevant for flat glass. Factors such as the area factor and edge factor are less relevant and applicable for container glass due to its inherent geometry. Thus, the design tensile strength of container glass cannot simply be calculated with the equation presented above. It must be obtained through experimental means. The load duration factor k_{mod} , which accounts for load duration effects is also different when considering these two types of glass.

According to NEN 2608:2014, the k_{mod} for flat glass can be calculated with:

$$k_{mod} = \left(\frac{t_0}{t} \right)^{\frac{1}{c}} \quad (4.2)$$

Where:

t_0 is the reference duration (taken as 5 seconds),

t is the actual load duration in seconds

c is the corrosion constant ($c = 16$)

When a design load of 50 years (equal to 1577880000 seconds) is considered, k_{mod} is calculated as follows:

$$k_{mod, \text{NEN2608}} = \left(\frac{5}{1577880000} \right)^{\frac{1}{16}} = 0.29 \quad (4.3)$$

AGR (American Glass Research) determined a load duration factor for long-neck glass beer bottles of $k_{mod} = 0.6$ for a load duration defined as 'long/warehouse', equivalent to a design load of 50 years [24]. This value is considerably higher than the flat-glass value derived above.

The load duration factor is a time-dependent coefficient that reduces the characteristic strength of glass under sustained loading. It accounts for stress corrosion caused by ambient moisture which reacts with the glass at the tips of micro-cracks, causing them to grow slowly over time and lead to the decrease glass strength.

Since the strength of the bottle is directly obtained from tests, the area, edge and surface factors are already contained in the measured value and can be taken as $k_a = k_e = k_{sp} = 1$. The design tensile strength of the bottle then follows as:

$$f_{t;d} = \frac{(k_{\text{mod, AGR}} \times f_{t;k})}{\gamma_{m;A}} \quad (4.4)$$

where $f_{t;k}$ is the characteristic tensile strength of the bottle, obtained for glass from a Weibull analysis. With the characteristic strength measured by AGR on bottles with severe abrasions, $f_{t;k} = 11.7$ MPa, the design strength becomes $f_{t;d} = 11.7 \times 0.6/1.6 = 4.39$ MPa.

4.2. Mechanical behavior of long-neck beer bottles under vertical loading

Destructive compression tests were performed at AGR in Delft to obtain the characteristic strength values of 330ml longneck beer bottles loaded in the direction of its axis. The bottles were intentionally damaged prior to the destructive testing to simulate wear and tear typically seen in a beverage factory using a line simulator, as well as damage caused by manual handling and abrasion. The line-simulated specimens reached an average compressive load value of 16.11 kN and a characteristic tensile strength of approximately 27 MPa. The manually abraded specimens reached an average compressive load of 17.30 kN and characteristic tensile strength of 20 MPa. The characteristics values were obtained by means of Weibull analysis. The majority of the tested bottles (28 units) fractured at the shoulder contact region. Under compressive load, rings of tensile principal stress form in the shoulder and heel region of the glass bottle [6][33].

4.3. Material properties of Earth Based Mortar

A study conducted at TU Delft developed self-compacting earth-based composites using locally sourced soil to produce bricks with an embedded glass bottle at their center. The research evaluated various mortar mixtures made with Dutch soil from Emmen, supplied by OSKAM V/F [5]. Five distinct earth-based mortar compositions were designed and tested. The selected mixture for brick production consisted of natural soil with the following constituent materials:

Table 4.2: Mixture proportions of Earth-Based Mortar with natural soil

Constituent materials	kg/m ³
Cement I 52.5 R	194.4
Natural soil	1550
Superplasticizer PCE	16
MasterGlenium 51	
Water	349

Since Earth Base Mortar is a relatively recent invention, the authors of the research made some assumptions where there is limited understanding on the mortar's material properties [5]. These assumptions, denoted by an asterisk (*), are based on existing data on low-strength concrete and rammed earth concrete, since they share similar failure patterns with that of the Earth-Based Mortar.

Table 4.3: Estimated material properties of Earth Based Mortar [5]

Material property	Value	Unit
Young's Modulus	2500*	MPa
Poisson's Ratio	0.2*	-
Tensile Ultimate Strength	12.2	MPa
Compressive Ultimate Strength	3.7	MPa
Density	1540	kg/m ³

4.4. Compressive testing of Glass Bottle Earth Bricks

Alkisaiei et al. (2024) conducted a study to investigate the potential of prefabricated earthcrete bricks embedded with a single glass bottle for the construction of load-bearing walls. The mechanical behavior of the embedded earthcrete bricks was analyzed using finite element method (FEM) modeling. Subsequently, prototypes were developed and tested in the laboratory to determine their compressive strength. The experimental methods and results are presented below.

Experimental testing

Three Glass Bottle Earth Bricks (GBEB) were cast with an earth-based mortar in a mold, containing a single glass bottle at the center. The molds were built using plates of multiplex as depicted in figure 4.1.a. The earth-based mortar was poured into the mold after the glass bottle was positioned vertically at its center. The average width and height of the 3 GBEB were 197 mm and 199 mm, respectively. The average depth is 223 mm with the block positioned as depicted in figure 4.1.c.

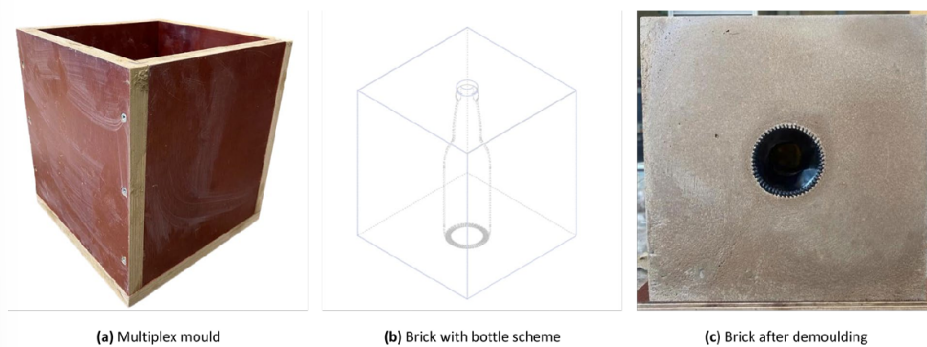


Figure 4.1: Production of the Glass Bottle Earth Brick (GBEB) [5]

After the curing duration of 28 days, compressive strength tests were conducted on each specimen at a compression rate of 6 kN/s. The test automatically stopped when no stress increments were noted. Physical experiments revealed a compressive strength ranging from 8.21 to 11.40 MPa. All samples showed similar circumferential failures in the heel region, which forced the heel to detach from the bottle during the experiment [5].

Numerical testing (FEM)

In the study, a 3D FEM of the GBEB (Glass Bottle Earth Brick) was conducted with SolidWorks. Boundary conditions were applied at the top and bottom surfaces of the block, as depicted in figure 4.2. On the upper surface, an external downward displacement of 0.1 mm was prescribed. In addition, interface conditions had to be applied to ensure collaborative numerical behavior between the mortar and the glass bottle, using the Mohr-Coulomb model. Furthermore, a coefficient of friction was assigned to account for the internal friction between the mortar and glass bottle. To obtain a high-quality mesh, triangular shell elements were used in combination with a blended-curvature-based mesher so that the element size could adapt to the relatively complex geometry of the bottle.

The numerical and physical experimental results showed strong agreement. The finite element analysis reveals that tensile and compressive stresses primarily concentrate on the bottle's inner surface. Cracks initiated on the outer surface, with failure predominantly occurring at the base and bottom of the glass bottle [5].

Given these results, the study concluded that it is feasible to produce Glass Bottle Earth Bricks (GBEB) for the application of structural walls [5].

4.5. Linear elasticity of glass

Glass is a brittle material, meaning it cannot dissipate stored energy through plastic deformation once the critical stress is reached. Instead, the accumulated energy is released through fracture.

This entails that glass exhibits approximately the behavior of a linear elastic material under typical

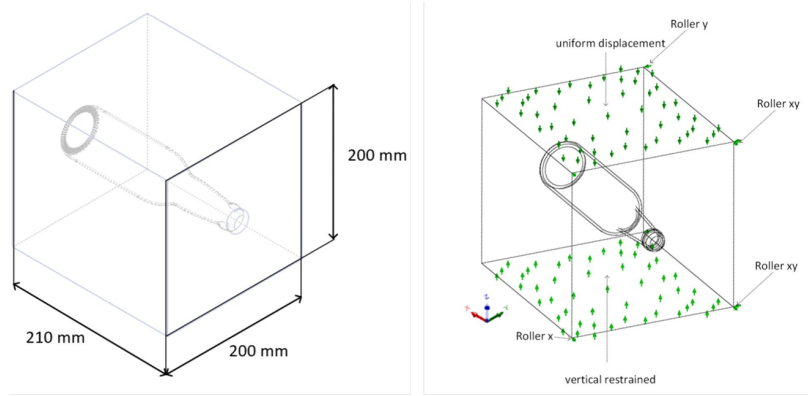


Figure 4.2: 3D FEM Earth-based mortar embedded with a single glass bottle [5]

loading conditions. Its isotropic material properties stem from the non-crystalline, amorphous atomic structure. The elastic stiffness matrix can be expressed through Equation 4.5, where:

- E denotes Young's modulus
- ν (ν) represents Poisson's ratio
- $\mathbf{D}$ is the 6×6 stiffness matrix

$$\mathbf{D} = \frac{E}{(1 + \nu)(1 - 2\nu)} \begin{bmatrix} 1 - \nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1 - \nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1 - \nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \quad (4.5)$$

$\mathbf{D}$ can be substituted into the following stress-strain relation:

$$\sigma = \mathbf{D}\varepsilon \quad (4.6)$$

5

Theory behind CDP and Brittle cracking models

This chapter contains a brief description of the FEM package that is used to model the composite units consisting of earthcrete and (an) embedded glass bottle(s).

Abaqus offers a wide range of models for simulating the behavior of materials. One of the models Abaqus provides is called Concrete Damage Plasticity (CDP). In this chapter, the theory behind the CDP model as well as the Brittle Cracking model and Concrete Smeared Cracking (CSC) is presented. It is important to gain understanding of these models to be able to simulate the mechanical behavior of materials such as glass and earthcrete under specific loading conditions.

Presently, there is limited literature on the mechanical behavior of glass bottles and earthcrete subjected to axial loading. One of the objectives of this project is to compare the behavior of the simulated models with the real behavior of the earthcrete and the glass bottles, obtained from experimental data, and to try to fit the model with parameter values which follows and describes the material behavior the best.

5.1. Finite Element Method: ABAQUS

Finite Element Method (FEM) can be performed using a wide range of software packages, each of which offer different benefits and/or drawbacks. In the field of structural engineering, the most commonly used software packages include ANSYS, SolidWorks, COMSOL and ABAQUS, with DIANA FEA also being widely adopted in the Netherlands for civil engineering applications.

When selecting software for this research project, one of the key considerations was the availability of a wide range of material property models that could be assigned to best simulate material behavior. Of the available options, ABAQUS was chosen due to its high node allowance and availability of a large amount of different material property models, making it the most suitable for the intended purposes.

ABAQUS is a finite element solver widely used in engineering and scientific research for simulating complex physical phenomena. A key strength of ABAQUS in structural engineering is its ability to handle complex nonlinear phenomena, including geometric nonlinearities (large deformations), material nonlinearities (plasticity, hyperelasticity, and creep), and contact nonlinearities (self- and general contact). Additionally, ABAQUS offers advanced capabilities for composite material modeling, including layered shell and solid elements with progressive damage criteria. Moreover, ABAQUS provides a highly flexible and extensible integrated user-friendly environment [1].

5.1.1. Explicit vs implicit time integration

Abaqus has both an implicit version called Abaqus/Standard and an explicit version (Abaqus/Explicit). In the implicit solver, Abaqus enforces global equilibrium at each increment by solving a large set of equations that drives the nodal forces to (or close to) zero. This approach makes each increment

much more expensive to solve compared to the explicit approach, where there is no need to enforce global equilibrium. In the latter (explicit) approach, the nodal displacements are extrapolated forward in time on the basis of existing velocity and acceleration, obtained from the resulting calculated force. Thus, the solver only needs to calculate the current local forces due to loads, deformation, damping, and inertia, without needing to find a zero-force solution.

Abaqus/Explicit uses a central difference rule to integrate the equations of motion explicitly through time. The program solves for dynamic equilibrium at the beginning of each increment by taking the nodal mass matrix, M , times the nodal accelerations, $\ddot{u}$, corresponding to the net nodal forces, which is the difference between the external forces, P , and internal element forces, I):

$$M\ddot{u} = P - I.$$

The accelerations at the start of the current increment (time t) are determined as

$$\ddot{u}|_{(t)} = (M)^{-1} \cdot (P - I)|_{(t)}.$$

The accelerations are then integrated through time using the central difference rule, which determines the change in velocity, assuming that the acceleration is constant. This change in velocity is then added to the velocity from the midpoint of the prior increment to obtain the velocities at the midpoint of the current increment:

$$\dot{u}|_{(t+\frac{\Delta t}{2})} = \dot{u}|_{(t-\frac{\Delta t}{2})} + \frac{(\Delta t|_{(t+\Delta t)} + \Delta t|_{(t)})}{2} \ddot{u}|_{(t)}.$$

The velocities are integrated over time and then added to the displacements from the start of the increment to obtain the displacements at the end of the increment:

$$u|_{(t+\Delta t)} = u|_{(t)} + \Delta t|_{(t+\Delta t)} \dot{u}|_{(t+\frac{\Delta t}{2})}.$$

To achieve accurate results with this method, the time increments must be small to ensure that the accelerations remain nearly constant within each increment. In return, explicit methods do not require convergence at any point. The present analyses contain brittle and quasi-brittle materials that undergo severe progressive damage in the post-peak phase, which is precisely the regime in which implicit equilibrium iterations tend to fail. For these reasons, Abaqus/Explicit was adopted.

5.2. Material models for simulating inelastic behavior

The ABAQUS library provides a wide range of constitutive models for simulating different material behaviors. Among these, Concrete Smeared Cracking (CSC), Brittle Cracking and the Concrete Damaged Plasticity (CDP) are typically used to simulate the inelastic response of brittle and cementitious materials [1][34]. Both CSC and Brittle Cracking, are based on a brittle fracture formulation. In the following section, the first two models are briefly discussed, detailing their underlying mechanical principles and drawbacks of application. Following this, an in-depth of the CDP model is presented as its capabilities render it more relevant to the present research.

5.2.1. Concrete Smeared Cracking (CSC)

The Concrete Smeared Cracking (CSC) model is a smeared crack model meaning that the model does not track individual "macro" cracks rather, it simulates cracks by adjusting the stress and stiffness at integration points. The CSC model is suggested to be used for applications in which the concrete is subjected to monotonic loading at low confining pressures. When specimens are subjected to cyclic loading, the CSC has difficulty in converging [38]. It can be used for plain concrete/earthcrete, even though it is intended predominantly for the analysis of reinforced concrete structures [48].

Plastic straining in compression is controlled by a compression yield surface. Cracking is assumed to be a key aspect of the behavior, and the representation of cracking and post-cracking anisotropic behavior dominates the modeling. The user may specify tension stiffening by a postfailure stress-strain relation or by applying a fracture energy cracking criterion. When the material is loaded in tension, it responds elastically up until a crack is formed. The CSC model represents a crack opening as a loss of its elastic stiffness [38]. The most significant advantage of this model compared to CDP model is the reduction of the computational cost. On the other hand, the main limitations of this model are related to the flow rule and the isotropic hardening, responsible for simplifying the response of the material [38].

5.2.2. Brittle Cracking

The "Brittle Cracking" model, normally applied to concrete, can be applicable to other brittle and quasi-brittle materials as well. In the brittle cracking damage model, a Rankine failure criterion is used for crack detection. The brittle cracking option is a "smeared model" which takes into account the presence of cracks into the constitutive calculations executed at each material point, in the form of stiffness degradation [9].

As previously discussed, glass is a material that is unable to yield plastically before fracture. This means that glass is very sensitive to stress concentrations caused by e.g. surface flaws. Consequently, glass is assumed to behave linear elastically until the maximum principal tensile stress exceeds the tensile strength f_t . Input parameters of this damage model used by a number of studies are a tensile strength of glass of $f_t = 45 \text{ MPa}$, a high nominal compressive strength of $f_c = 1000 \text{ MPa}$ and a fracture energy set equal to $G_f = 3 \text{ J/m}^2$ [9][23]. Moreover, post-cracked behavior was described with "brittle shear", which is a suboption available in ABAQUS.

The standard Brittle Cracking model is designed for a complete and abrupt loss of strength. This is a good model to simulate the mechanical behavior of glass bottles which are tested in isolation. However, as experimental data has shown, the glass bottles embedded in earthcrete exhibit some level of post-peak residual strength, meaning that the confinement and interaction with the earthcrete matrix enable continued minor load transfer through mechanisms such as interlocking of glass fragments and interface friction.

For earthcrete this model is not suitable, as it lacks any mechanism to represent compressive nonlinearity.

5.3. Concrete Damage Plasticity Model

The 'Concrete Damage Plasticity' model ('CDP' in the following), although originally developed for reinforced concrete, is also well-suited for simulating other materials that show quasi-brittle behavior such as earthcrete and brittle materials such as glass [11]. Quasi-brittle materials typically feature a large fracture-process zone and fail predominantly by fracturing rather than yielding.

In the CDP model, the failure potential function is derived from the Drucker-Prager model, modified to take into account the varying evolution of strength under compression and tension [11]. The model assumes two failure mechanisms, namely tensile cracking and compressive crushing of the material. The two hardening variables that control the evolution of the yield surface are: the tensile equivalent plastic strains, ε_t^{pl} and compressive equivalent plastic strains, ε_c^{pl} .

The CDP model assumes that the response of the material, subjected to uniaxial tensile and compressive loading, is characterized by damaged plasticity, as depicted in figure 5.1.

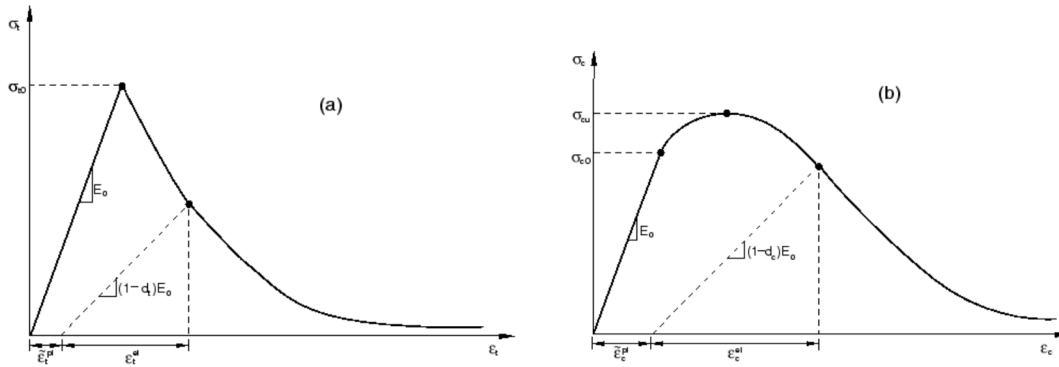


Figure 5.1: Response of concrete to uniaxial loading in tension (a) and compression (b) [1]

5.3.1. CDP Model: Nonlinear compressive behavior

Under uniaxial compression, the stress-strain response follows a linear elastic relationship until the value of initial yield σ_{c0} . As the load increases, the response will start to exhibit non-linear or a plastic regime characterized by irreversible deformation that remains after the applied load is removed. Initially,

the plastic regime will contain a stress hardening regime, followed by a strain softening regime beyond the ultimate stress σ_{cu} . In the strain softening regime, after the peak strength has been reached, the material becomes weaker as deformation continues. When the load is increased further, cracks and damage will develop further, leading to reduced stiffness and load-bearing capacity [21]. Whereas earthcrete may have a more progressive nonlinear behavior, glass's fracture is sudden and without prior warning. The typical load-carrying behavior of glass under compression can be divided into two separate phases. The elastic uncracked stage and the crack propagation stage or inelastic stage, where the cracks form instantaneously. This second phase is negligible. For both of these materials, it is important to create an accurate model of the (nonlinear) behavior to be able to obtain a precise mechanical analysis of the composite blocks. The compressive stress-strain behavior is obtained by assigning values to the following parameters:

- σ_c is the total compressive strain
- ε_c^{in} is the inelastic strain.
- d_c is damage variable which characterizes the level of degradation of the elastic stiffness in the CDP model. Damage variables range from 0 to 1, representing the undamaged and complete damage of the material, respectively.
- E_0 is the initial (undamaged) elastic stiffness of the material.

The compressive inelastic strain is defined as the total compressive strain ε_c subtracted by the elastic strain ε_{oc}^{el} , corresponding to the undamaged material.

$$\varepsilon_{oc}^{el} = \frac{\sigma_c}{E_0} \quad \longrightarrow \quad \varepsilon_c^{in} = \varepsilon_c - \varepsilon_{oc}^{el} \quad (5.1)$$

The stress-strain relation of the material can be calculated as follows:

$$\sigma_c = (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl}) \quad (5.2)$$

5.3.2. CDP Model: Nonlinear tensile behavior

The stress-strain response of quasi-brittle and brittle materials under uniaxial tensile loading is initially characterized by a linear elastic relationship, up until the value of the failure stress σ_{t0} is reached. Tensile failure in quasi-brittle material is initiated by the onset of micro-cracking, progressively increasing in size and number. Beyond the failure stress, the onset of micro-cracks is represented with a softening stress-strain relationship. In this regime, strains are induced, comprising the fracture process zone as depicted in figure 5.2.

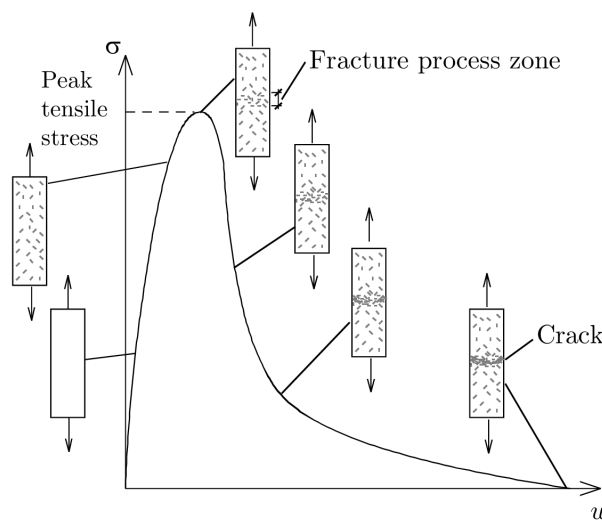


Figure 5.2: Formation of micro-cracks under uniaxial tensile loading. Reproduction of Bjornstrom et al. (2006) [35]

As shown in Figure 5.1, when a concrete specimen is unloaded from any point on the strain softening branch of the stress-strain curves, the unloading response is weakened, meaning that the elastic stiffness of the material has a certain amount of damage (or degradation) [21].

In ABAQUS there are three different methods for defining the post-cracking behavior, namely by:

- Strain which can be defined by entering the postfailure stress/cracking-strain relationship.
- Displacement which can be defined by inputting the postfailure stress/cracking-strain relationship.
- GFI which stands for Gradient Failure Index and can be defined by entering the failure stress, σ_{t0} (units of FL^{-2}) and the Mode I fracture energy, G_f (units of FL^{-1}).

A value is also assigned to Tension Damage or else if it is omitted, the model behaves as a plasticity model. The method selected for defining the tensile damage variable "Strain" to define the tensile damage variable as a function of cracking strain.

In the compression recovery field a value can be assigned ranging from 0 to 1, representing the amount of compression stiffness that is recoverable as the loading changes from tension to compression. If ω_c is zero, no stiffness is recovered.

The tensile cracking strain ε_t^{ck} is defined as the total tensile strain ε_t subtracted by the elastic strain ε_{ot}^{el} , corresponding to the undamaged material.

$$\varepsilon_{ot}^{el} = \frac{\sigma_t}{E_0} \longrightarrow \varepsilon_t^{ck} = \varepsilon_t - \varepsilon_{ot}^{el} \quad (5.3)$$

The tensile stress-strain relation of the material can be calculated in a similar manner to the compressive stress-strain relation, namely:

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl}) \quad (5.4)$$

Tension softening

As previously mentioned, in finite element analyses, the formation of micro-cracks to macro-cracks is achieved numerically by implementing a crack opening law, often referred to as tension softening. The crack opening law is typically defined with a stress-strain or stress-displacement relationship or also in terms of fracture energy.

In some cases, the approach based on a stress-strain relationship may lead to unreasonable mesh sensitivity. Meaning that if a localization of cracking is present, the post-cracking behavior will differ significantly depending on the chosen mesh size. To address this problem, Hillerborg (1976) devised a fracture energy proposal that can be applied to effectively reduce mesh sensitivity [25].

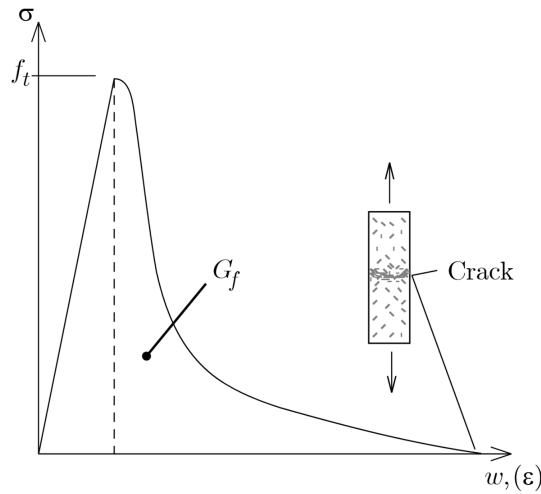


Figure 5.3: Fracture energy and crack formation [35]

The fracture energy approach utilizes the material parameter G_f , which represents the energy required to open a crack per unit area of the fracture surface. Numerically, G_f corresponds to the area under the post-peak stress-displacement ($\sigma-u$) curve, representing the energy absorbed within the damage zone, to obtain a stress free crack. The area underneath the curve marked by G_f as depicted in figure 5.3 corresponds thus to the fracture evolution stage. This diagram can be obtained by measuring the residual tension stress versus crack width and can be determined by performing a three-point bending test.

There exist some scientific studies, albeit small in number, that have examined the post-peak behavior of glass. These studies typically include a secondary material bonded to the glass, which allows for residual strength of the glass in the post-peak phase [11][12]. For instance, a finite element study on post-tensioned SG-laminated glass beams with mechanically anchored tendons utilized ABAQUS to model and analyze the post-cracked behavior of glass [10]. The tensile behavior in this study was defined using a "GFI" and a *Concrete Tension and Compression Damage* model with a displacement-based softening law. The key parameters for glass were a tensile strength $\sigma_t = 45$ MPa, a compressive resistance $\sigma_c = 1000$ MPa and a fracture energy $G_f = 3$ J/m². According to the formula given in the ABAQUS manual, this results in a cracking displacement of $u_{ck,t} = u_{ck,c} = 2G_f/\sigma_t = 1.33 \times 10^{-4}$ mm, at which point the tensile damage was set to $d_t = d_c = 0.8$. A compression recovery factor of $\omega_c = 0$ was specified. Attempts to reproduce a model with the provided parameters failed due to convergence errors from negative plastic strains in the Compression Damage model. This suggests that the documented parameters for Compression Damage are likely incorrect or were changed at a later date and not revised before publication.

Moreover, according to Wiederhorn et al. (2006), the values for the fracture surface energies can range from 3.5 to 5.3 J/m², depending on the chemical composition of the glass and the temperature at which the test is conducted [23]. Given this variability, a sensitivity analysis on this parameter is carried out in the following chapter.

5.3.3. Fracture energy of concrete

Concrete, as a quasi-brittle material, is capable of sustaining decreasing levels of stress after cracking. Initially, tensile stresses induce a band of micro-cracks, known as the fracture process zone. Upon reaching the material's tensile strength, these micro-cracks merge to form a dominant macro-crack. Beyond this point, the tensile capacity of the concrete decreases but is not eliminated due to mechanisms like aggregate interlock, which provide residual strength [28]. The macro-crack then propagates through the section, bypassing or crossing aggregates until ultimate failure occurs.

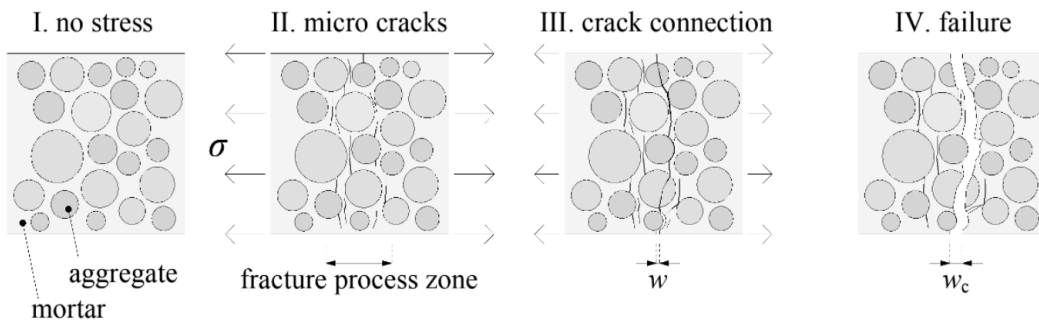


Figure 5.4: Crack propagation in concrete [28]

The fracture energy of concrete is frequently specified in literature as a function of strength class and maximum aggregate size, as depicted in table 5.1. The abaqus manual provides a few values for the fracture energy of concrete, namely G_f of 0.04N/mm for $\sigma_c=20$ MPa and G_f of 0.12N/mm for $\sigma_c=40$ MPa

[1].

For concrete, the fracture energy can be estimated using the formula provided in the CEB-FIP Model Code [32], as follows:

$$G_F = G_{F0} \frac{f_{cm}}{f_{cm0}} \quad (5.5)$$

Table 5.1: Base values of fracture energy G_{F0} [32]

$d_{\max}$ (maximum aggregate size) [mm]	G_{F0} [N/mm]
8	0.025
16	0.030
32	0.058

The earthcrete mixtures used by H. Heller [2024] and Hoessein Alkisaie contained no aggregates, relying instead on natural soil with a maximum particle size of 1–2 mm. Fracture energy should then potentially be lower than the values described above.

5.3.4. CDP Parameters

The CDP model requires the definition of five material model parameters, namely dilation angle (ψ), eccentricity (ε), the proportion between initial biaxial compressive strength to the uniaxial one (f_{b0}/f_{c0}), the shape factor (K) and the viscosity parameter (μ). For new materials such as earthcrete, these parameters are particularly difficult to estimate due to lack of knowledge or experimental data. To understand the influence of these parameters on the material response, a literature review is carried out, in particular with regard to concrete. The findings of this review establish a baseline understanding on how these parameters can be calibrated.

Dilation Angle (ψ)

The dilation angle is measured in the p-q plane under conditions of high confining pressure. This angle dictates the ratio of plastic volume change to plastic shear strain [42]. A higher dilation angle signifies higher dilatation and consequently also a greater volumetric expansion during plastic deformation.

Reinforced concrete has an optimal dilation angle of 31° under both compression and tensile stress conditions [21]. Materials such as soil, concrete and rock typically exhibit dilation angles close to 20°. As such, materials with a more brittle behavior have a smaller dilation angle. For example, recycled concrete aggregate which typically has a more brittle behavior, has a lower dilation angle with values ranging from 5 to 10 degrees [20].

To the knowledge of the author, the literature reporting the values for the dilation angle of glass is limited. Some studies (on polymers) approximate the dilation angle as equal to the friction angle (β), for simplicity or due to lack of experimental data [42]. However, Vermeer and Borst (1984) [49] observed that for materials such as soils, rocks and concrete, the dilation angle is typically significantly smaller compared to the friction angle of the material. Given the material's negligible plastic deformation and abrupt fracture mechanics, the dilation angle for glass is expected to fall within a low range of 0° to 5°.

The formula to calculate the dilation angle is given by:

$$\psi = \frac{\delta \epsilon_v}{\delta \gamma} \quad (5.6)$$

Several studies such as [35], [41], [43] have analyzed the influence of dilation angle in CDP models. In [35] the impact of different dilation angles is examined for a 3D solid model of a long beam subjected to a 4-point bending test. For smaller values of the dilation angle, the behavior of the concrete becomes more brittle. For angles close to the material friction angle, the material behavior becomes more ductile, as depicted in figure 5.5. When changing the dilation angle, the position of the first yielding point in the force-displacement curves remains fixed as it only affects the plastic strains. Consequently, the post

elastic response changes significantly with the dilation angle [43]. Moreover, [41] concluded that for cubic unreinforced concrete blocks, the dilation angle only affects the uniaxial compressive stress-strain response in the softening portion after a certain strain value.

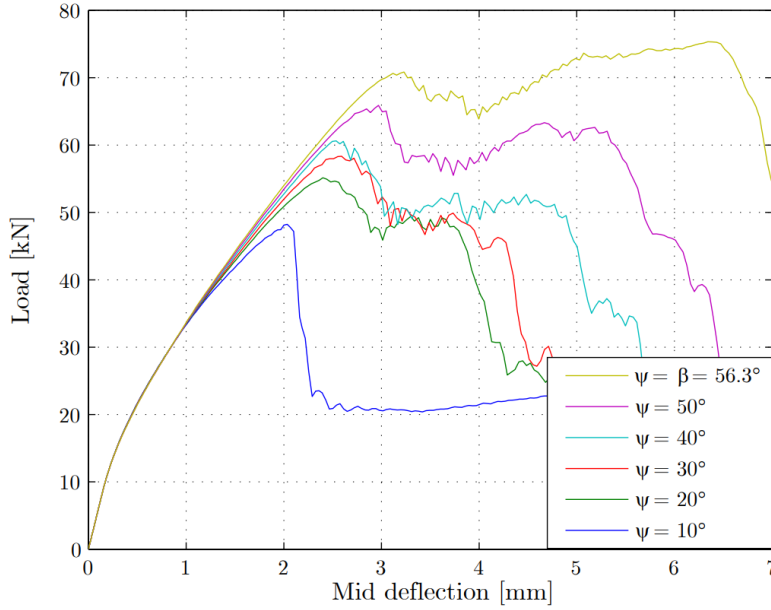


Figure 5.5: Influence of the dilation angle in CDP models [35]

Eccentricity (ε)

The parameter ε defines the eccentricity of the plastic potential surface in accordance with Bazant and Jirasek's formulation. The default flow potential eccentricity is 0.1, which indicates that the material has almost a constant dilation angle when subjected to different confining pressure stress values [21]. A high value of the eccentricity corresponds to high curvature of the flow potential [43]. To the best of the authors knowledge, no sensitivity studies have been carried out on the impact of varying values of eccentricity on the response of concrete to compressive testing.

The ratio of biaxial to the uniaxial compressive yield stresses

The ratio of initial equibiaxial to the uniaxial compressive yield stress is a parameter that describes the characteristics of the failure function. The default value in ABAQUS is typically 1.16 for concrete.

$$f = \frac{f_{b0}}{f_c} \quad (5.7)$$

The ratio of the second stress invariant on the tensile meridian to that on the compressive meridian

According to Kmiecik and Kamiński [31], the "parameter Kc is interpreted as a ratio of the distances between the hydrostatic axis and respectively the compression meridian and the tension meridian in the deviatoric cross section." The triangular deviatoric plane suggests a lower degree of confinement, whereas a circular indicates a high degree of confinement. The parameter γ is typically between $\frac{2}{3}$ and 1 [21].

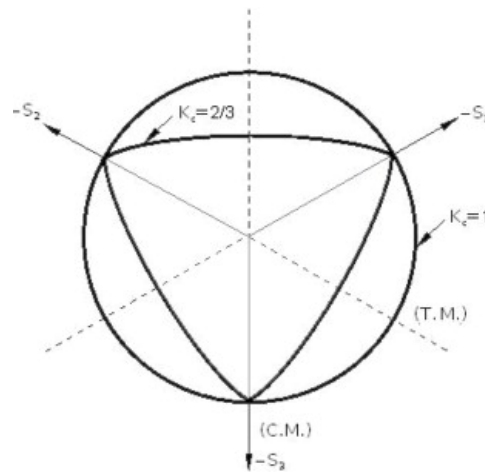


Figure 5.6: Deviatoric cross section of failure in CDP [31]

Viscosity Parameter

This parameter helps improve the rate of convergence in the softening phase in implicit analyses. In Abaqus/Explicit no such regularization is needed, thus the viscosity parameter is set to zero.

Discussion of the material model parameters

The material model parameters that is most likely to have the most effect on the material behavior in the post-peak phase is Tension Damage and Compression Damage parameters. The dilation angle could also possibly have an effect on the post-peak behavior of the composite unit.

Compared to glass, concrete typically has a significantly larger fracture process zone. For glass the post-failure stress-displacement curve can be approximated to a linear decay to zero stress over a very small strain/displacement [2].

NUMERICAL INVESTIGATIONS

6

Finite Element Method (FEM) modeling of a single glass bottle (and earthcrete blocks)

In this chapter, the mechanical behavior of an individual glass bottle is investigated, establishing important insights for the ensuing chapters and analyses. Firstly, the results from experimental tests are presented, followed by a description of the geometry, material properties and mesh used in the FEM models. The values of the CDP parameters inputted within this section are adjusted accordingly to best simulate the results obtained from the experimental data.

6.1. Mechanical behavior of vertically loaded glass bottles

Experimental tests conducted at the Stevin Lab by Hoessein Alkisaie revealed some important insights into the mechanical behavior of glass bottles under uniaxial compressive loading. Seven tests were carried out until complete failure was reached. Analysis of the resulting force-displacement data, as depicted in figure 6.1, yields an average fracture load of 42790.83 N . Furthermore, the structural stiffness of the bottles was calculated to be 65231.91 N/mm , which in this case represents the slope of the $F - u$ graph.

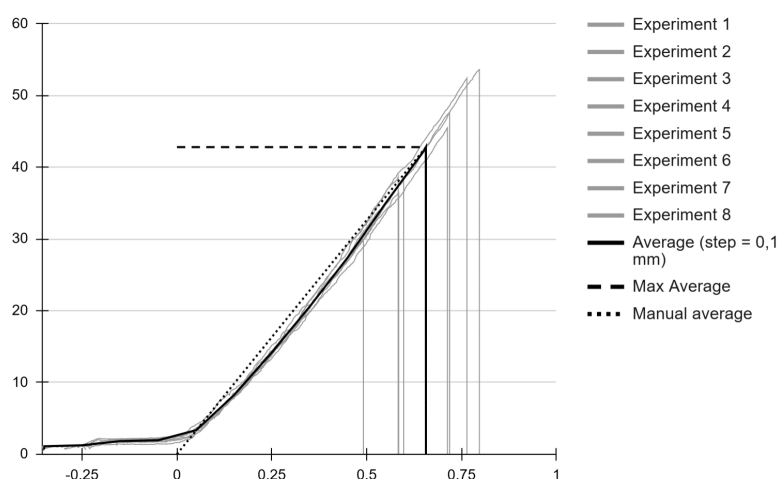


Figure 6.1: Force-displacement graph of axially loaded bottles (in vertical direction) [3]

As established in Chapter 4 and illustrated in Figure 6.1, glass exhibits classic linear elastic-brittle failure. This behavior is characterized by a linear force-displacement response up to the peak load. After this point, fracture occurs, resulting in an instantaneous drop of the $F - u$ graph. Consequently, the material exhibits a negligible post-peak inelastic branch when tested in isolation.

Failure consistently initiates at the shoulder region of the bottle. This localization is attributed to a combination of factors: a locally reduced wall thickness of 2.8 mm, the inherent presence of microscopic surface flaws that act as stress concentrators, and the geometric curvature of the shoulder itself. The geometric curvature is responsible for i.e. generating bending stresses, with the outer surface being in tension [29]. With the resulting average peak force obtained from experimental testing, a preliminary estimate mean axial compressive stress over the shoulder cross-section can be calculated as follows:

$$\begin{aligned}\sigma &= \frac{F}{A_{\text{shoulder}}} = \frac{F}{\pi [R_{\text{outer}}^2 - (R_{\text{outer}} - 2.8)^2]} \\ &= \frac{43697.96}{\pi \left[\left(\frac{61.0}{2} \right)^2 - \left(\frac{61.0}{2} - 2.8 \right)^2 \right]} \\ &= 85.36 \text{ MPa}\end{aligned}$$

A resulting longitudinal stress value of 88.56 MPa is obtained. This result, however, ignores bending/curvature effects and eccentricities which is precisely why FEM should be employed.

6.2. FEM of a single glass bottle

6.2.1. Geometry

On the manufacturer's specifications an average overall thickness of 3,4 mm of the bottle is specified. However, manual measurements indicate large discrepancies in thickness between different parts of the bottle. As such, two different geometries will be investigated: one where the bottle's geometry is modeled with a constant thickness of 3,4 mm denoted as bottle B and one with variable thickness denoted as bottle A, according to the manual measurements, both depicted in Fig. 6.2.

The model presented here is a simplified version of the actual bottle design. Notably, it does not include knurls at the base, which have been replaced by a flat contact surface that interfaces with the support. The influence of knurls is considered negligible once the container is embedded within the earthcrete matrix. Moreover, the geometry of the finish of the bottle (located above the neck) is simplified to a single straight line since the extrusions have no significant influence on the results. The heel of the bottle, normally concave, is modeled as a flat surface to distribute the stresses more evenly and prevent the occurrence of stress singularities. In Appendix C, the variant with a concave bottom is discussed further. Additional geometric specifications are provided in appendix A.

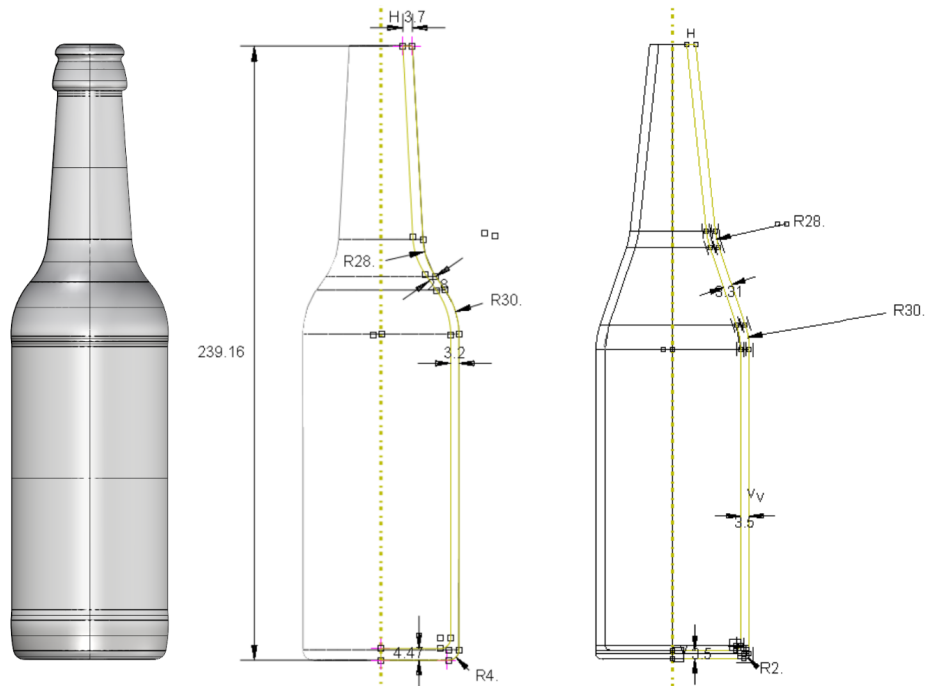


Figure 6.2: True geometry of the long-neck beer bottle (left) compared to two the simplified models (middle (B) and right (A))

6.2.2. Material properties

The material properties as described in Chapter 4 are for abraded glass under long-term loading, corresponding to a long-term characteristic tensile strength of 11.7 MPa.

The present model uses unabraded glass under short-term loading, justifying a higher tensile strength. This adjustment accounts for the absence of sustained loading over extended periods (e.g. 50 years), which would otherwise induce static fatigue (gradual crack growth), leading to strength degradation in the glass. Furthermore, due to the different bottle geometries in this study, the stiffness parameters must also be re-calibrated for the new model.

Taking the average of the fracture loads, the yield stress, compressive stress and damage parameters can be approximated for the two geometries. For geometry A, a glass yield stress of 37MPa is given. For geometry B, the glass strength needed to be increased to 70 MPa to obtain a fracture load close to the average one. Because the thickness at the shoulder is 2.8 mm, instead of 3.4 mm, the glass strength needs to be increased accordingly.

In the table below, the material properties for the respective models are given:

Geometry	Glass Tensile Behaviour		Glass Tension Damage	
	σ_t (MPa)	ε_{cr}	d_t	ε_{pl}
Geometry A	37.0	0.000	0.000	0.000
	0.37	8.40×10^{-4}	0.990	3.0×10^{-5}
Geometry B	70.0	0.000	0.000	0.000
	0.70	1.54×10^{-3}	0.990	2.0×10^{-5}
	Glass Compressive Behaviour		Glass Compression Damage	
	σ_c (MPa)	ε_{cr}	d_c	ε_{pl}
Geometry A	800.0	0.000	0.000	0.000
	400.0	8.80×10^{-3}	0.500	1.0×10^{-5}
Geometry B	800.0	0.000	0.000	0.000
	400.0	8.80×10^{-3}	0.500	1.0×10^{-5}

Table 6.1: CDP tensile and compressive behavior with damage parameters.

6.2.3. Meshing

The 3D models were meshed with four-node linear tetrahedral elements (C3D4 in Abaqus) with first-order accuracy. As illustrated in Figure 6.3, each tetrahedral element is defined by four vertices and six edges.

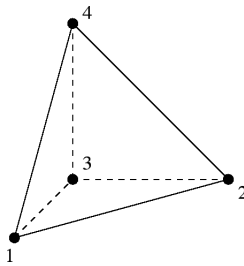


Figure 6.3: Four-node linear tetrahedral elements (C3D4) [18]

Other mesh types such as quadratic tetrahedrons (C3D10 and C3D10M) were also considered, as they offer improved accuracy for curved geometries. However because these mesh types are more computationally expensive, it was deemed excessive for the scope of this research project.

For Bottle B, three models with identical material properties but varying mesh densities were analyzed in Abaqus. As illustrated in Figure 6.4, the results exhibit some mesh sensitivity.

The 2 mm mesh, although providing higher geometrical accuracy, requires substantially more computational cost. The coarse 10 mm mesh proved to give a lower fracture load compared to the 5 mm mesh. It must be noted that symmetry was used going through the center of the bottle to obtain the results for the 2 mm

mesh. Because the model was halved, the force was halved also effectively modeling half the physical stiffness of the full model. This is corrected by multiplying the F by 2 (see figure 6.6). A 5 mm mesh size was selected for the first part of the simulations in this research, representing an adequate balance between computational efficiency and result accuracy.

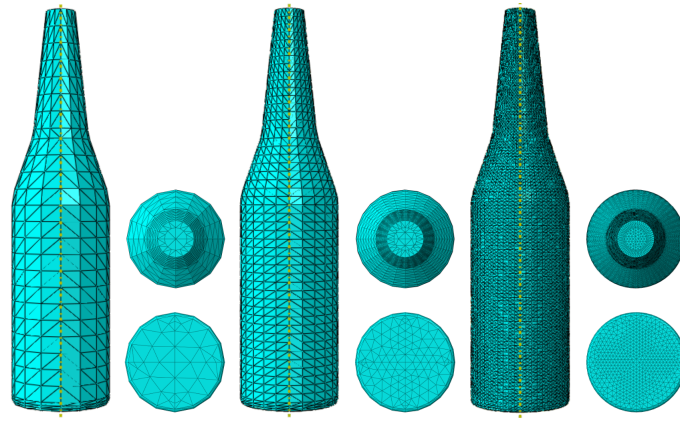


Figure 6.4: Mesh sizes of Bottle A: 10 mm (left), 5 mm (middle) and 2 mm (right)

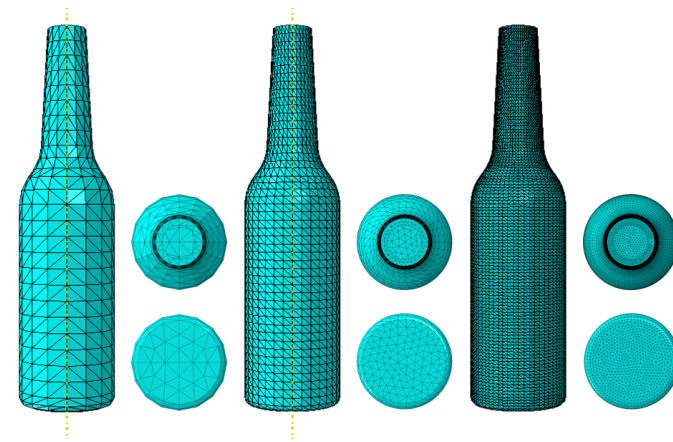


Figure 6.5: Mesh sizes of Bottle B: 10 mm (left), 5 mm (middle) and 2 mm (right)

It is important to note that when refining the mesh (e.g., from 5 mm to 2 mm), the corresponding material properties, particularly the tensile strength (input as the CDP yield stress), must also be re-calibrated. The properties used for the 5 mm mesh are specific to that mesh size. These properties were calibrated so that the simulated fracture load fits the experimental average fracture load. The material properties and mechanical behavior of glass will be discussed in detail in the next sections.

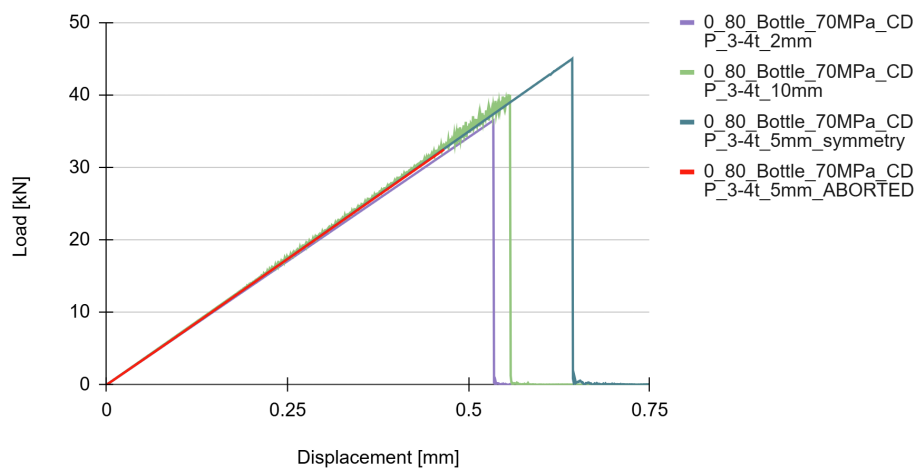


Figure 6.6: Fracture load versus mesh size Bottle B

6.2.4. Principal Stresses

The maximum principal stress (σ_1) is tensile in nature and is critical for failure prediction, especially for brittle materials such as glass. If (σ_1) exceeds the material's tensile strength, cracking is likely to initiate.

At shoulder region high tensile stresses (σ_1) develop due to bending and abrupt curvature changes. The shoulder region is often the weakest point, making it most susceptible to crack initiation. At the body region, circumferential/hoop stresses develop under axial compression. The heel of the bottle is also prone to higher tensile stresses oriented in the circumferential direction.

The analysis reveals a stress singularity at the load application point. This singularity arises due to the discrete nature of finite element modeling, where point loads create theoretically infinite stresses that do not reflect physical reality.

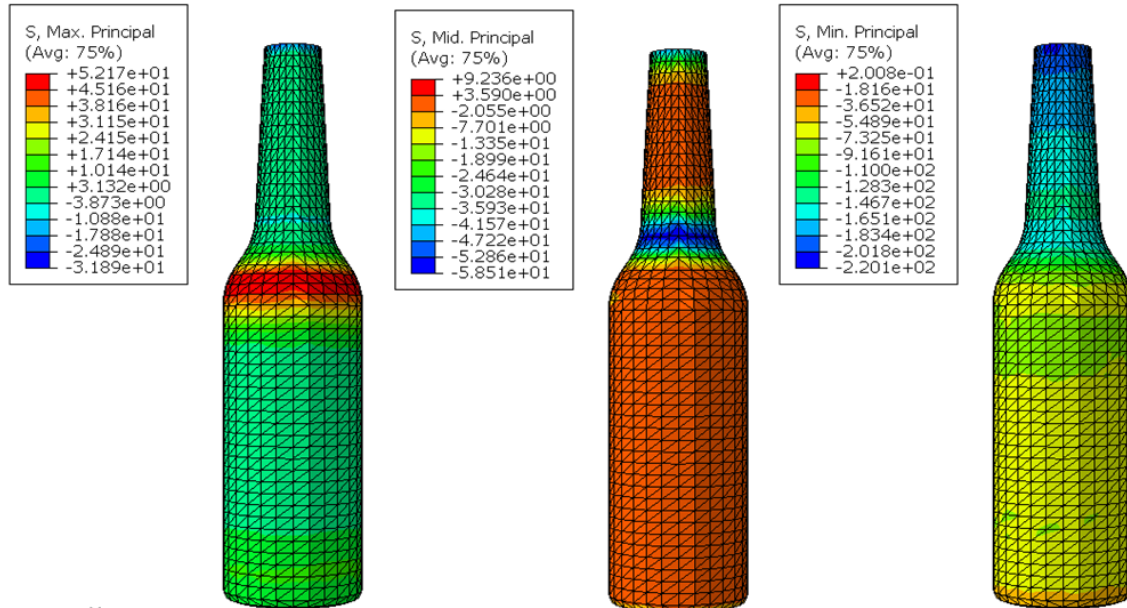


Figure 6.7: Principal stresses

6.2.5. Crack pattern DAMAGET and DAMAGEC (Bottle B)

As previously discussed, the damage parameter quantifies the degradation of material stiffness. The complete fracture of the bottle at the shoulder occurs within a time increment of 0.001 seconds, which is the prescribed output time interval at which results are saved. The crack pattern shows higher density primarily at the shoulder region, where the maximum principal stresses are highest and the wall thickness is 2.8 mm. The damaged zone extends over a comparable area under both the tensile and compressive damage outputs, as depicted in figure 6.9. In the model, at a time step of 0.6330, several nodes were observed to "explode" outward at the shoulder region. According to the Researchgate community, this behavior is not uncommon in Abaqus Explicit simulations. A probable explanation of this phenomenon is that once the glass fails, the local stiffness is greatly reduced, causing the force acting on certain nodes to gain very high accelerations. Since these nodes belong to elements that have already failed and no longer transfer forces, the phenomenon has no real physical meaning and does not compromise the validity of the results.

It is worth noting that once the glass is embedded within the matrix, these nodes are subject to additional constraints that help to potentially prevent this phenomenon. The crack pattern is consistent with experimental observations: the glass fractures irregularly, fragmenting into small pieces.

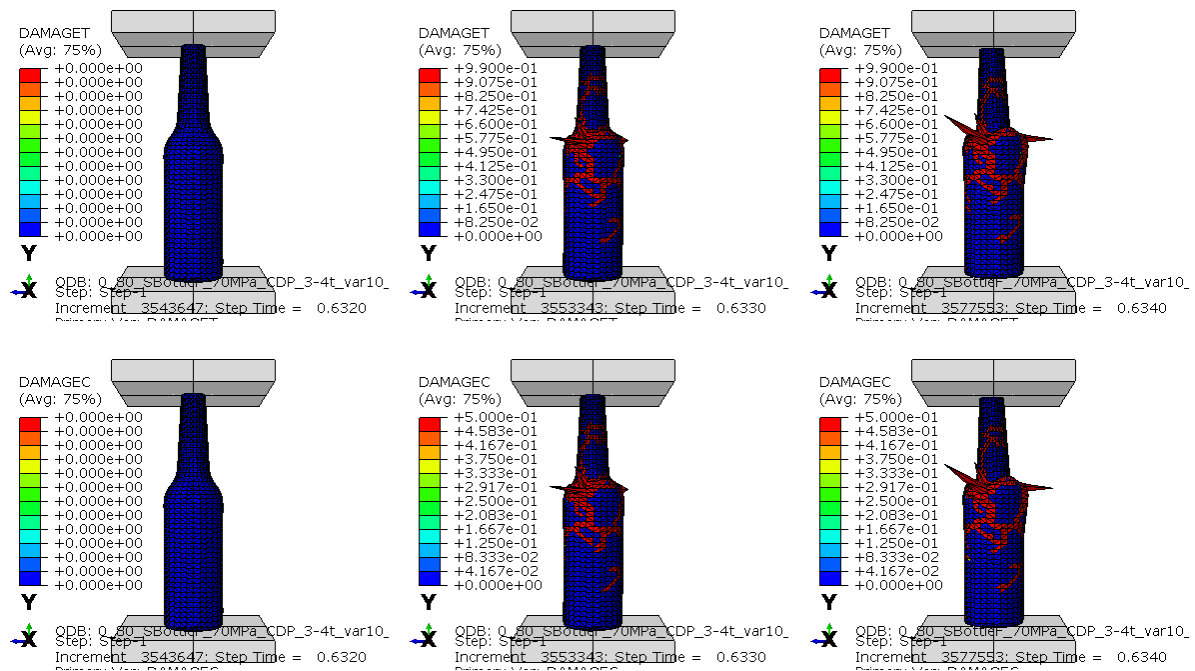


Figure 6.8: Damage tension

The bottle with tensile strength 70MPa has a fracture force of 44.1 kN (vs experimental mean 43.7 kN, +1.0%). The tensile strength of glass is almost double compared to that of Bottle A due to the lower thickness at the shoulder region of 2.8 mm instead of 3.4 mm.

Discussion

The initial GBEB model embedded with Bottle B geometry failed to replicate the correct mechanical behavior seen in the experiments. Consequently, a switch was made to earthcrete blocks embedded with the Bottle A geometry modeled by Hoessein Alkisaie, featuring a uniform thickness of 3.5 mm. While this geometry is not a precise representation of the experimental specimens, it produces load-displacement curves that fit significantly better with the experimental data.

6.2.6. Crack pattern DAMAGET and DAMAGEC (Bottle A)

The figure below visualizes the tensile and compressive damage distributions. The damaged regions for both damage types largely overlap. For the 10 mm mesh, the majority of glass fractures occur at the shoulder of the bottle.

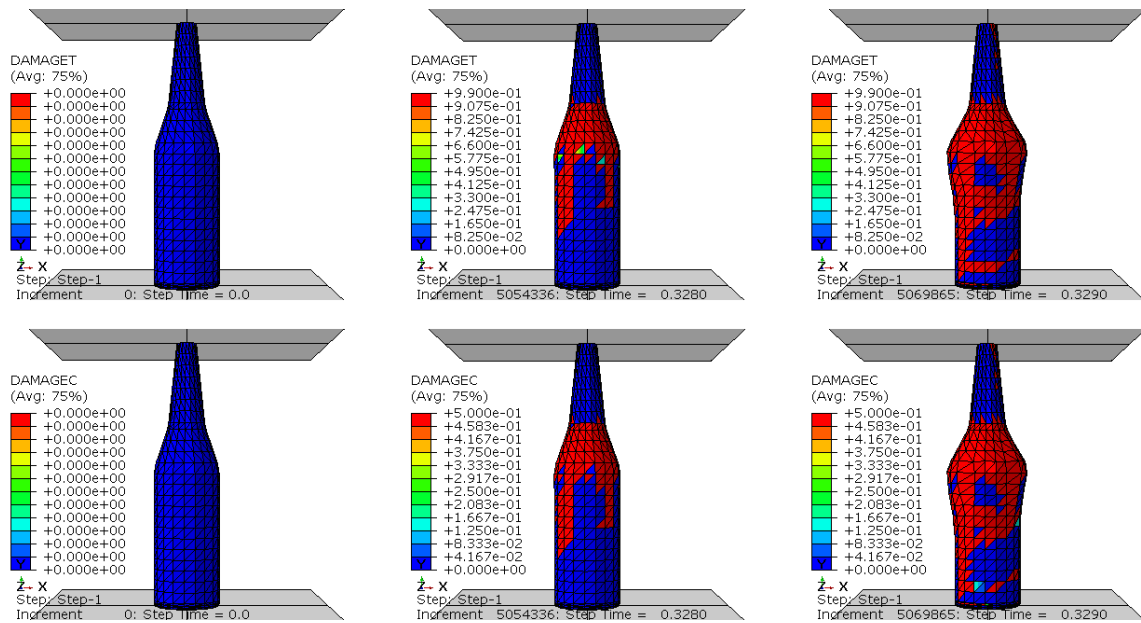


Figure 6.9: Tensile damage (top row) and compression damage (bottom row) 10 mm mesh of Bottle A

6.3. Effect of changes to Tensile & Compression Damage in glass with a 10 mm mesh

In figure 6.10 the tensile damage is fixed at 99% and the increase of the compressive damage parameter from 50% to 99% leads to a reduction in the fracture load. The response for the 4 tested options remains brittle, losing complete capacity after the peak-load has been reached. Notably, the peak load does not follow a monotonic trend, as peak load is higher for 75% compression damage than for the 99%, 50% and 25%.

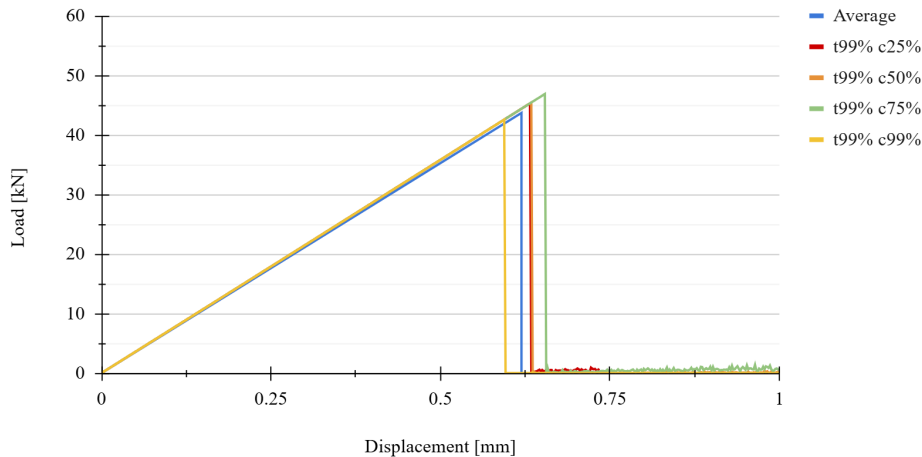


Figure 6.10: Constant tensile damage of 99% with variations in compression damage

Conversely, when the compressive damage is maintained at a constant value of 50% (depicted in figure 6.11 and the tensile damage is increased from 25% to 99%, the material exhibits a noticeably more ductile behavior in the post-peak regime. By limiting compressive stiffness degradation to 50%, the material can undergo significant deformation while sustaining slightly increasing applied loads, reaching almost a plateau-like state. A similar trend occurs when tensile damage is fixed at 50% and compress-

sive damage is varied from 25% to 99%: lower compressive damage yields a more ductile post-peak response.

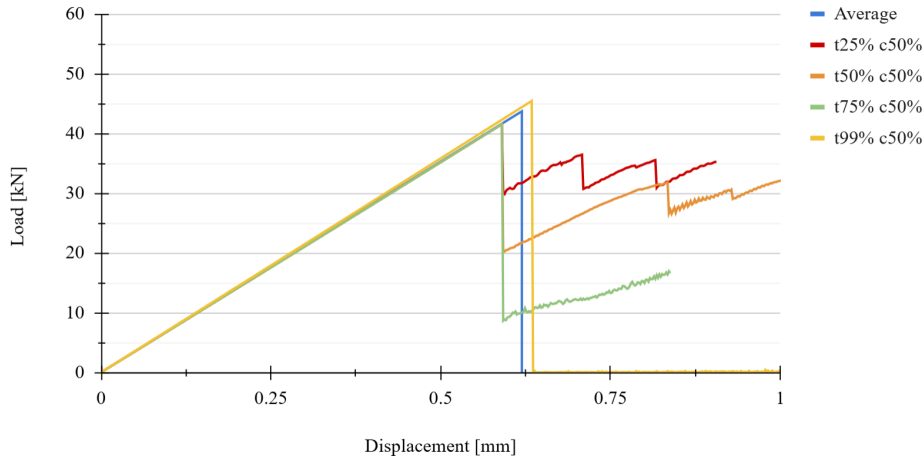


Figure 6.11: Constant compression damage at 50% with variations in tensile damage

6.4. Fracture energy of glass

As previously discussed in Chapter 4, the fracture energy of glass is typically reported in literature as 3 J/m^2 , which corresponds to 0.003 Nmm/mm^2 . This value was adopted as a baseline for modeling the glass bottle with a mesh of 10 mm and calibrated to obtain valid results. Figure 6.12 illustrates the load-displacement responses obtained for different fracture energy values. Some noticeable observations can be made. First, increasing the fracture energy leads to a more gradual failure process: instead of a sudden breakage, the glass exhibits progressive damage over an extended displacement period. Second, the peak load increases with higher fracture energy, which indicates that there is a strong sensitivity of the model to the fracture energy approach (GFI). For fracture energy values between 0.002 and 0.004 Nmm/mm^2 , the post-peak behavior does not reflect real glass fracture mechanics. As shown in the upper row of captured snapshots in figure 6.13, the stiffness degradation is distributed for the most part at the shoulder region, with tensile damage parameter taking intermediate values between 0 and 99%. In reality, glass fails along discrete crack paths, while the remaining material remains undamaged. This discrepancy can be attributed to the relatively coarse mesh (10 mm) which is not able to capture localized cracking well. Consequently, these higher fracture energy values are considered unrealistic.

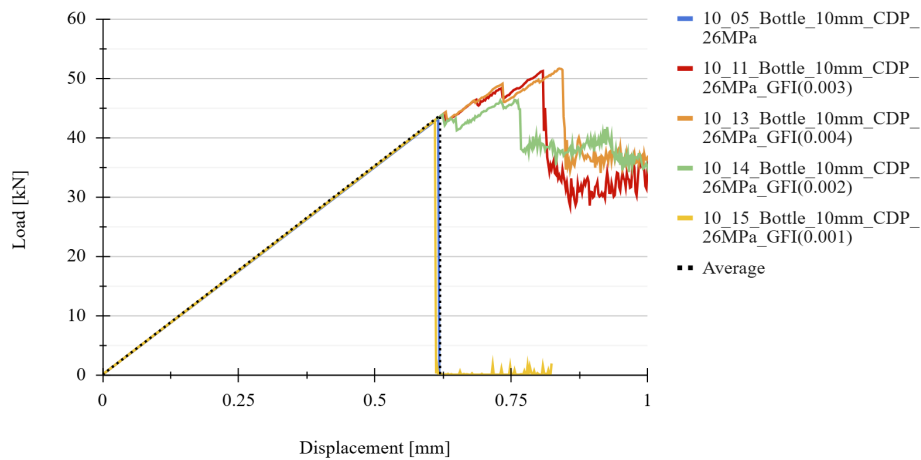


Figure 6.12: Sensitivity analyses of GFI for a glass bottle with mesh size 10 mm

Lowering the fracture energy to 0.001 Nmm/mm^2 yields more plausible results concerning its mechanical behavior. At this value, the peak load aligns well with the expected failure load of glass obtained by averaging the experimental tests. With a GFI value of 0.001 Nmm/mm^2 , no residual strength is observed after fracture which is consistent with the brittle nature of unconstrained glass.

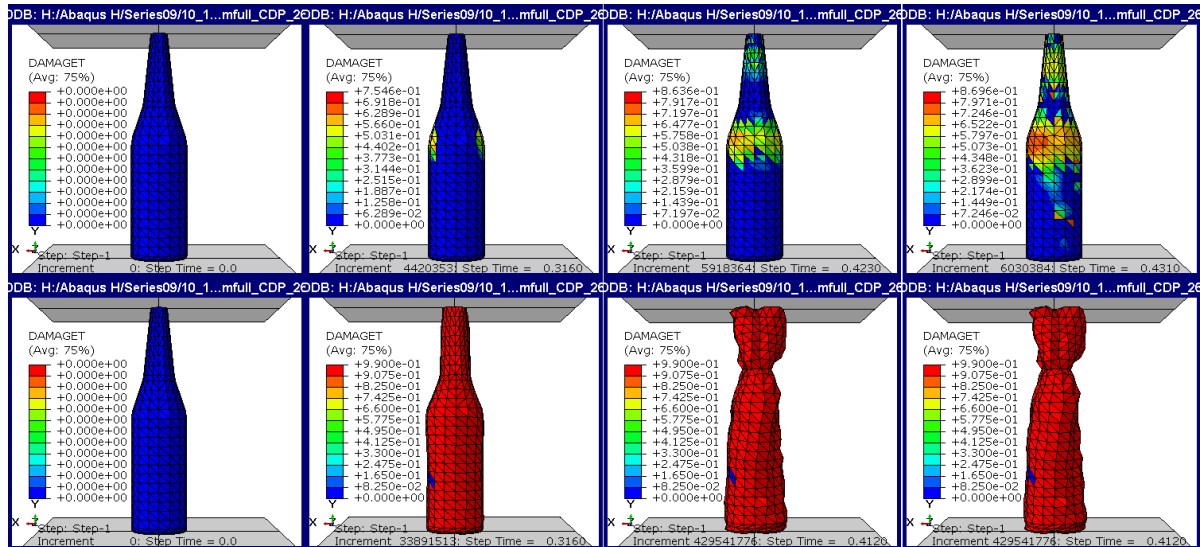


Figure 6.13: Progressive damage of a glass bottle with mesh size 10 mm using GFI 0.004 N/mm (upper) and 0.001 N/mm (lower)

Interestingly, when using a fracture energy of 0.001 Nmm/mm^2 , the load at which the bottle breaks does not affect only the shoulder region but the entire bottle as well (lower row of snapshots). This raises questions regarding the validity of the results, as the observed overall damage distribution does not align with the expected localized failure at the shoulder in the glass bottle as discussed earlier.

In subsequent chapters, a comparison will be made between GBEB models using a fracture energy of 0.001 Nmm/mm^2 and those relying solely on tensile and compressive damage parameters.

I. Numerical investigations of earthcrete blocks embedded with a glass bottle

This chapter investigates the interaction between earthcrete matrix and an embedded glass bottle under compressive loading. A model of the composite unit with standard dimensions is created in ABAQUS, and its mechanical behavior is analyzed through compression tests. The model is subjected to a downward displacement applied at the top of the unit, parallel to the bottle's axis. The study aims to evaluate stress distribution and propagation within the composite unit as well as understand potential failure modes.

The advantage of conducting numerical investigations prior to experimental investigations, is that it enables the testing of a greater number of variants in a relatively shorter time-frame provided that computer capacities are sufficient. Additionally, numerical investigations provide valuable insights into stress concentrations and potential crack propagation patterns. These findings are crucial for the experimental phase of the study, as they allow for strategic placement of strain gauges in critical regions. The FEM results and underlying assumptions will be validated through analytical calculations and sensitivity studies. Moreover, the FEM results will also be correlated with experimental data detailed in Chapter 9.

7.1. Representative load-deflection curves from experimental data

At Stevin Lab, Hoessein Alkisaie conducted a series of compression tests on earthcrete units embedded with glass bottles, loaded in the vertical orientation. From these tests the most representative force–deflection curves were selected for use in this study.

7.1.1. Load-deflection curve of GBEB with vertical bottle

Figure 7.1 shows three load-displacement curves of vertically oriented GBEBs, together with their average, obtained from uniaxial compression tests. The response is characterised by two primary phases: an initial linear-elastic phase followed by an inelastic phase. In the linear-elastic phase the load rises proportionally with deflection and the small spikes along this branch mark the first fractures in the glass. The inelastic regime can be divided into two phases: the deflection hardening phase (region A) and the post-peak deflection softening phase (region B). In region A, the glass continues to fracture and as the load increases, micro-cracks start to form and propagate through the earthcrete, developing into macro-cracks up until a critical fracture occurs. This fracture is marked by a sudden and significant drop of the load-displacement curve at 2.25 mm. Once the glass has failed completely, the earthcrete matrix becomes the sole load-carrying component. In region B, the earthcrete enters into the deflection softening phase where its load-carrying capacity begins to decrease greatly until the unit disintegrates.

For comparison, the graph also includes the average curve of an identical block without an embedded bottle. Both block types pass through the same three phases: linear-elastic, deflection-hardening and deflection-softening. They also show near-identical stiffness. Despite glass being stiffer than earth-crete, its presence does not significantly stiffen the block. The embedded bottle does, however, reduce the peak load-bearing capacity by 22.2%.

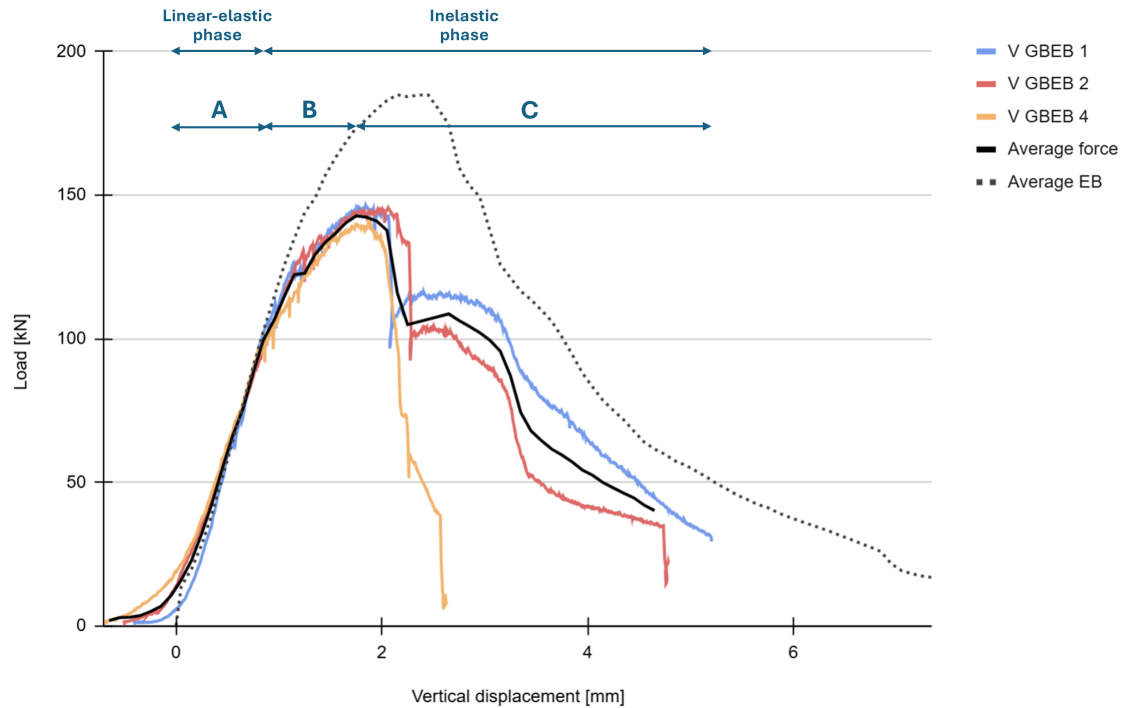


Figure 7.1: Load-displacement of GBEB and EB [3]

7.2. Modeling in FEM

Detailed finite-element (FE) simulations are carried out in ABAQUS to attempt to simulate the real mechanical behavior of the composite unit under compressive loading. Boundary conditions and interface conditions are applied to best represent actual physical conditions.

Modeling methodology

The model consists of a longneck beer glass bottle (as described in Annex A) embedded within an earth-crete block. To ensure a well-defined interface between the two materials, the overlapping earthcrete region within the outer boundary of the glass bottle was removed using a Boolean subtraction operation. The initial earthcrete unit measures 150 mm in width and depth and 240 mm in height. These dimensions will be adjusted later on when testing different configurations.

Boundary conditions

The model's boundary conditions are defined as follows: the bottom face is constrained in all directions ($u_x = u_y = u_z$). Because C3D4 solid elements have translational DOF only, Abaqus will ignore all imposed rotational constraints such as $\varphi_x = \varphi_y = \varphi_z = 0$). Two cases are considered for the lateral boundaries. The first case leaves them unconstrained. The second case constrains their normal displacement to simulate the block being part of a larger monolithic structural element or placed adjacent to other blocks with mortar.

Interface conditions

In ABAQUS there are a number of different ways the interface between the glass and the earthcrete can be modeled. The choice of contact definition is important, as it influences the failure propagation and stress concentrations in the GBEB. The relevant contact types for this research are detailed below:

- **Fully Bonded** This formulation does not allow separation or sliding between faces. It assumes perfect adhesion, creating a fully constrained interface. This method is typically used when there is certainty that the bond is much stronger than the two adjoining materials. In ABAQUS, this is realized by merging the geometries into a single, monolithic part. As it cannot capture debonding, this approach is likely to over-predict the block's overall strength and stiffness.
- **Surface-to-Surface Contact (Frictional)** This approach allows for more realistic interactions. When "hard" contact is specified for the "Normal Behavior", it prevents the glass from penetrating the earthcrete, allowing the surfaces to separate when contact pressure becomes zero. For a weak bond a friction coefficient is specified using a *Penalty* formulation set to 0.3. A review of the current literature reveals no established value for the friction coefficient between glass and earthcrete.
- **Cohesive Zone Model (Advanced Debonding)** This approach simulates failure at the interface and is thus ideal if progressive debonding is expected. It requires defining a *traction-separation law* that specifies the interface's strength and fracture energy. The separation occurs along a predefined interface and cannot propagate in other arbitrary directions.

Initially, the blocks will be modeled with Fully Bonded interface conditions. This choice is made primarily to ensure quicker numerical convergence, especially during the initial testing phase. The Fully Bonded approach eliminates contact nonlinearity and has a simpler numerical formulation. However, this computational efficiency comes at the cost of physical accuracy, as it prevents the simulation of debonding.

Meshing

A consistent global mesh size of 5 mm was adopted to balance computational efficiency with result accuracy. The mesh consists of linear-order tetrahedral (C3D4) elements, consistent with the mesh mentioned in Chapter 6.

External loading

In general, two distinct methods exist for applying external loads in computational models. The first approach, known as load control, involves applying the load in a number of steps. The second method, known as displacement control, involves prescribing progressively increasing displacements to the model. This causes stresses to develop within the specimen, which in turn generates corresponding nodal forces at the location of the displacement application. Summation of these nodal forces yields the total reaction force, equal in magnitude but opposite in direction to the externally applied load resulting from the prescribed displacements. Usually, when looking at creep problems, loads will be prescribed rather than displacements. For other problems displacement control is typically preferred. This preference stems from two key advantages of this method: first, a faster convergence behavior of the iterative procedure can be attained, especially for non-linear computations, and second, it avoids the potential singularity of the tangential stiffness matrix that often occurs under load control. This singularity of the matrix typically arises at local maxima or global failure points in the load-deflection diagram [13]. Thus the loading of the blocks will be done through displacement control. A displacement of 10 mm is prescribed to the upper horizontal surface of the unit. The overall output frequency of the following tests is set to 0.001 units of time.

7.3. Influence of different glass properties on the response curve of the FEM model with Bottle B

7.3.1. Changing the tensile strength of glass

As the nominal strength of the glass is increased from 37 MPa to 70 MPa and finally to 100 MPa, the peak load of the composite block increases correspondingly, as depicted in figure 7.2. In the elastic phase, both the earthcrete and the glass contribute to transferring the compressive load to the support, albeit not equally. Due to glass's higher stiffness it acts as the dominant load-bearing material in the block. The failure of the glass is marked by a sudden and significant drop in the load-displacement curve, after which load transfer shifts primarily to the earthcrete matrix in the post-peak regime.

Right after the point of peak load, the glass exhibits a tension damage of 99% and a compression damage of 94% as specified in ABAQUS, primarily localized at the shoulder area. The specified compression damage causes a degradation of the localized stiffness, meaning that the glass material can no longer sustain the majority of the compressive stresses. Following the glass failure, the earthcrete exhibits a consistent behavior in all three cases, with its post-peak response being relatively similar across the different glass strengths. After the earthcrete reaches its ultimate strength (around 3 mm), the material follows a softening phase, characterized by a gradual decay in load-bearing capacity.

A comparison with experimental data reveals discrepancies in the simulated load-displacement response of all three models. Specifically, they fail to capture the inelastic phase (rounding) that precedes the peak load. Furthermore, the simulated softening phase of the earthcrete exhibits a more gradual slope than is observed experimentally. This means that the earthcrete input properties are more ductile than the experimental data. Since none of the three variants replicate this behavior, additional models must be developed and tested.

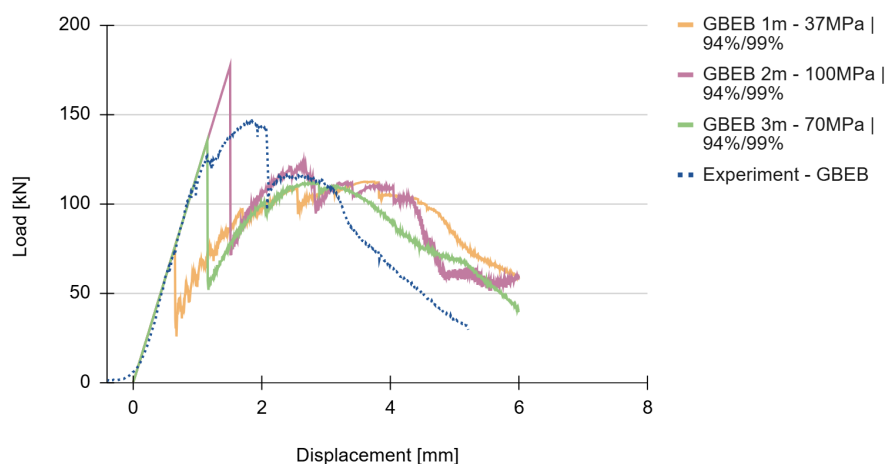


Figure 7.2: Load-displacement of GBEB with different glass strength values [4]

7.3.2. Changing the damage values of glass 37 MPa

With the glass tensile strength fixed at 37 MPa, modifying its damage parameters alters the composite's inelastic response and peak-load value. The results demonstrate that a lower compression damage (e.g., 50% compared to 94%) and lower tensile damage (50% compared to 99%) permits the fractured glass to remain active in load transfer even after a significant fracture has occurred, implying continued load transfer between glass elements, interlocking and possibly friction between particles.

Model [GBEB 5m - 37MPa | 50%/50%] was terminated due to diverging results from the experimental curve.

Model [GBEB 6m - 37MPa | 50%/99%] gives promising results with a compression damage of 50% and a tension damage of 99%. Notably, this material model does not capture the load drop observed at approximately 2 mm displacement, which is attributed to earthcrete cracking. Further investigation will examine whether modifying the earthcrete material properties can reproduce this dip in the response

curve.

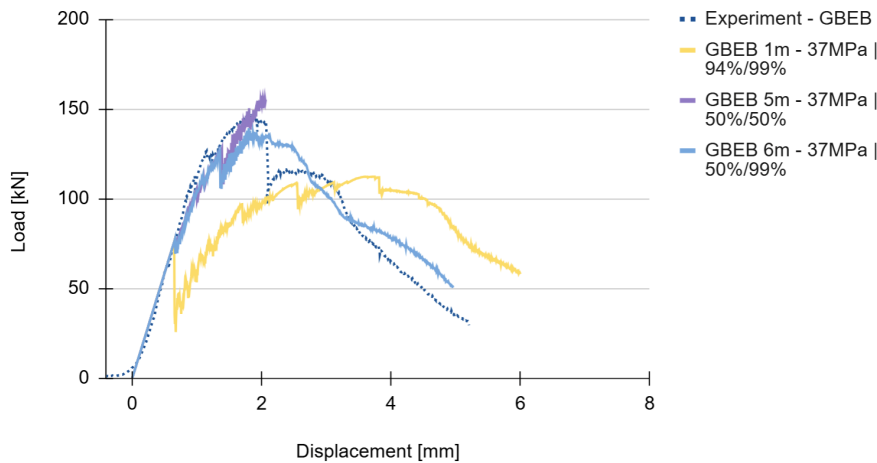


Figure 7.3: Load-displacement of GBEB with different damage values of glass (37MPa) [4]

7.3.3. Changing the damage values of glass 70 MPa

The numerical analysis reveals that altering the damage parameters for tension and compression yields a similar load-displacement response pattern for both 70 MPa and 37 MPa tensile glass strengths. As anticipated, the model with the higher tensile strength (70 MPa) predicts a greater peak load. The numerical simulations indicate that reduced damage values extend the duration of the non-linear phase and thus also increasing the peak-load. Model 4 and 5 were terminated due to diverging results from the experimental data. A comparison with experimental results reveals that none of the simulations provide an accurate fit.

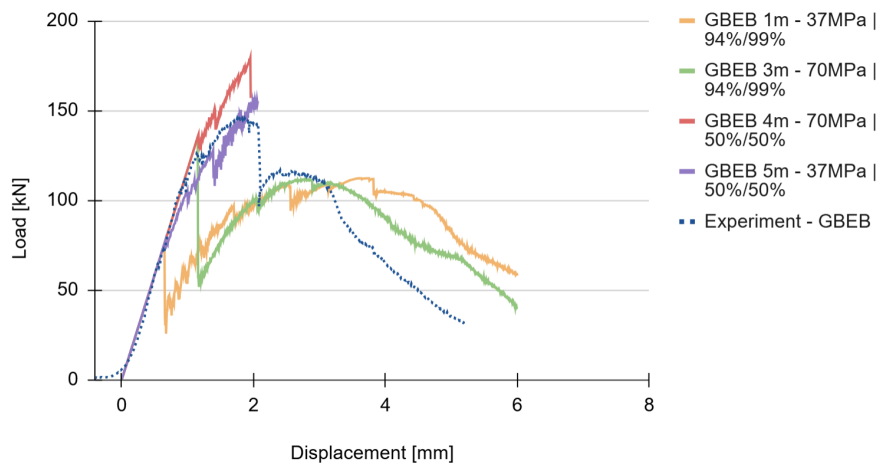


Figure 7.4: Load-displacement of GBEB with different damage values of glass (37MPa and 70MPa) [4]

Discussion

Model [GBEB 6m - 37MPa | 50%/99%] yields the best match to the experimental data among the models tested. To improve the fit further, the next step is to refine the model's parameters. It is important to note that the experimental curve shown above is a representative specimen, selected as a median response and not an average of all tests. Hence, it would have been sufficient to continue further research with Model [GBEB 6m - 37MPa | 50%/99%]. However, to gain further insights as to why the

model responds as it does, it is best to continue calibrating parameters to determine what improves accuracy.

7.4. Influence of the earthcrete material model on the FEM response curve

The earthcrete material parameters used in this work originate from a calibration study by Hoessein Alkisaiei, in which a series of simulations was performed to reproduce the average force–displacement response of plain earthcrete cubes of $40 \times 40 \times 40$ mm (without an embedded bottle). From that study, parameter set *EC34* provided the closest fit to the experimental average.

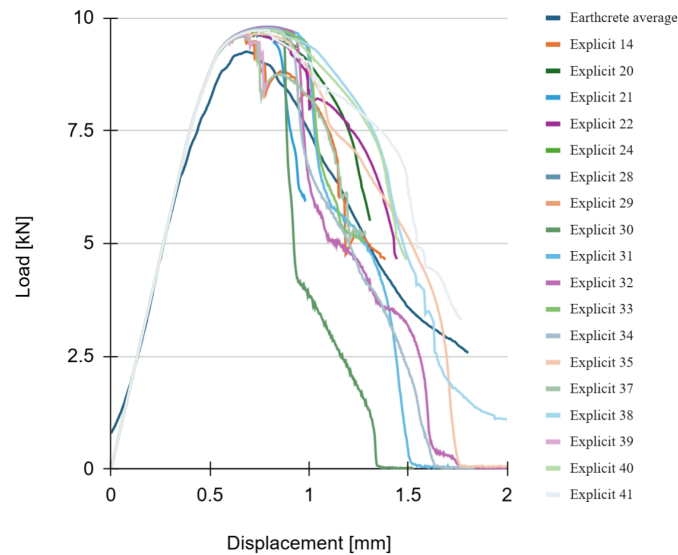


Figure 7.5: Earthcrete material models tested by Hoessein Alkisaiei

From the variants, three material models were selected for testing within the GBEB model: EC32, EC34 and EC37. The primary difference between them lies in the assigned tensile yield strength, the cracking strain and the tensile damage evolution. The parameter sets are listed in Table 7.1 and Figure 7.6 shows the calibration variants that lay closest to the experimental mean.

Material properties	Concrete Tensile Behaviour		Concrete Tension Damage	
	σ_t (MPa)	ε_{cr}	d_t	ε_{pl}
EC 32	4.0	0.000	0.000	0.000
	0.275	9.0×10^{-3}	0.93125	6.3×10^{-4}
EC 34	3.0	0.000	0.000	0.000
	0.03	8.0×10^{-3}	0.990	1.33×10^{-3}
EC 37	2.0	0.000	0.000	0.000
	0.02	9.434×10^{-4}	0.99	8.385×10^{-4}

Table 7.1: Concrete tensile and compressive behavior with damage parameters.

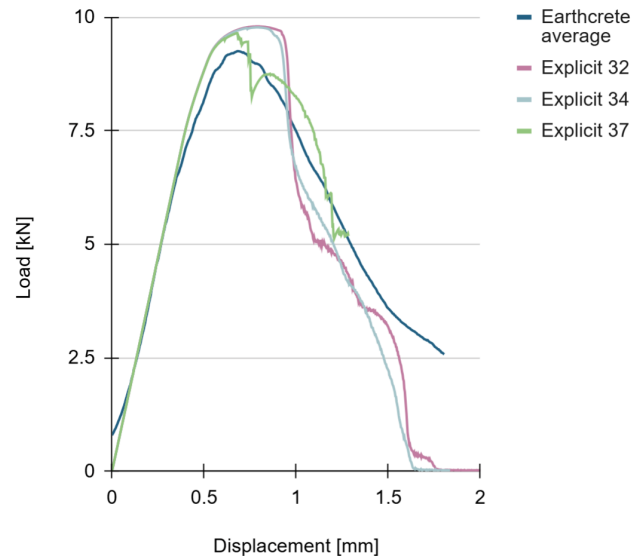


Figure 7.6: Earthcrete variations

Before transferring these parameters to the GBEB model, some key points deserve comment. The calibrations above were carried out on small plain cubes, whereas the GBEB is substantially larger and contains an embedded geometry. Quasi-brittle materials exhibit size effects which affect the strength and the brittleness of the post-peak response. So a material parameter set calibrated for a 40 mm cube is not guaranteed to reproduce the behavior of the full block.

The tensile softening branch in the Concrete Damaged Plasticity (CDP) model is defined here through a stress–cracking-strain relation (Table 7.1). Thus, the transferability is only valid if the same mesh size is maintained.

Simulating the GBEB with the three parameter sets alters its mechanical behavior significantly, as shown in Figure 7.7. The EC37 model was terminated at approximately 2 mm of displacement because its response diverged excessively from the experimental results. The EC32 model, by contrast, is the only variant that reproduces the characteristic load dip at approximately 2 mm of displacement observed experimentally.

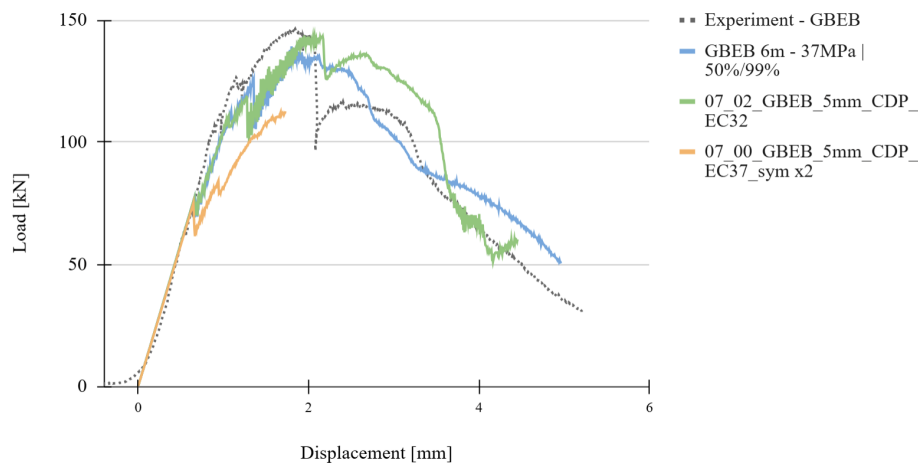


Figure 7.7: GBEB with different earthcrete variations (32, 34 and 37)

Analysis of the tensile damage in the EC32 model at the load dip (Figures 7.9 and 7.8), reveals that crack propagation, visualized here as tensile damage, initiates predominantly at shoulder height of the outer surfaces and advances inwards. This damage pattern is attributed primarily to the failure of the embedded bottle at its shoulder in the preceding time steps: once the bottle loses integrity, the earthcrete matrix loses its internal support and caves outward under increasing displacement. The full progression of tensile damage can be seen in Appendix D.

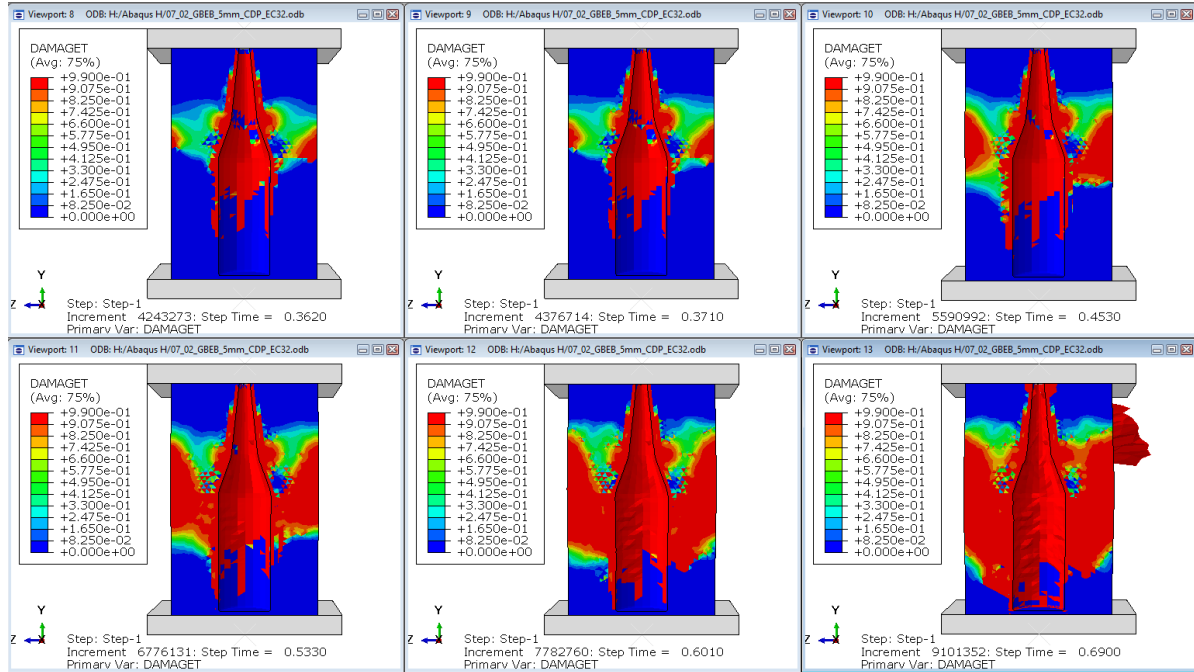


Figure 7.8: Vertical cross-section of the GBEB with tensile damage evolution at 6 different points shown also in Figure 7.9 (5mm mesh)

The tensile damage plots alone, however, do not explain why this variant exhibits a pronounced dip where the others do not. The equivalent plastic strain (PEEQ), a scalar measure of the accumulated inelastic deformation, provides some clarity on this front (Figure 7.9).

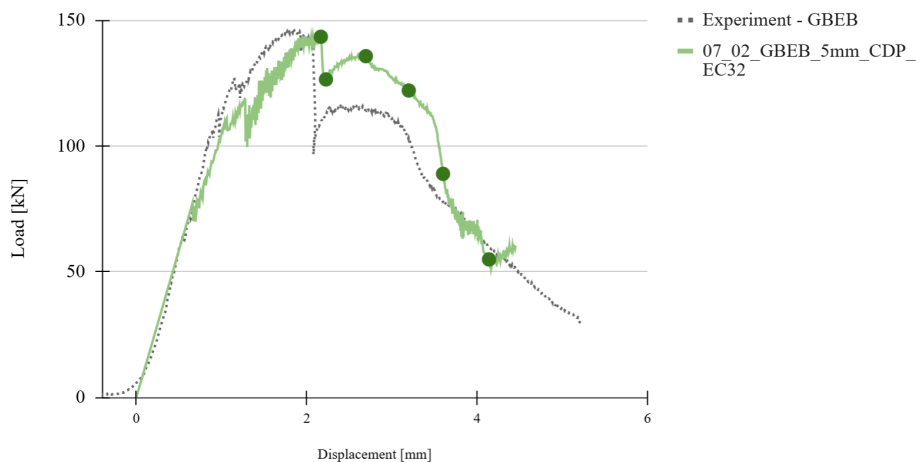


Figure 7.9: GBEB with tensile damage evolution - points in Fig. 7.8

Immediately after the dip, at step time 0.3710 (represented by the second column of figures), a concentration of plastic deformation develops at the top of the bottle in the neck region, where PEEQ increases

e.g. from 0.0043 to 0.0126 in node 4217 (located at the top of the neck). The same node does not displace in the vertical direction between these two time steps, indicating that the plastic deformation occurs in the horizontal direction. This is confirmed by the fact that node 4189, at the most linker part of the bottle displaces from 0.0243291 to 0.0482164 mm. The proposed failure mechanism consists thus of a brittle failure which causes a sudden loss of internal support (momentary drop in load) followed by re-stabilization of the load path.

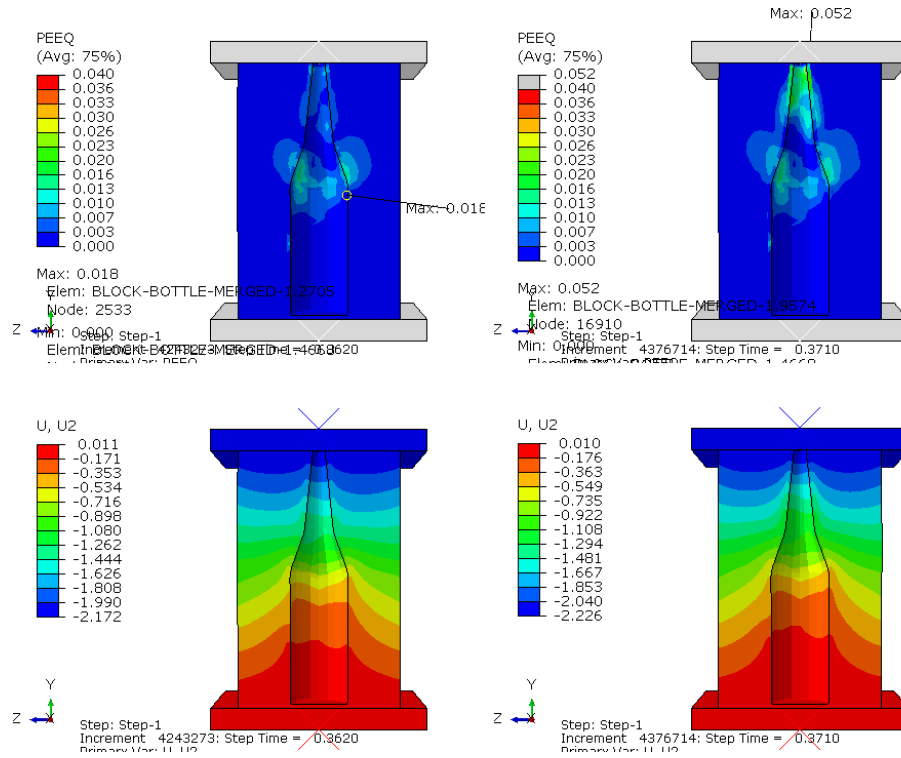


Figure 7.10: GBEB with PEEQ (first row) and U2 (second row) evolution at the dip

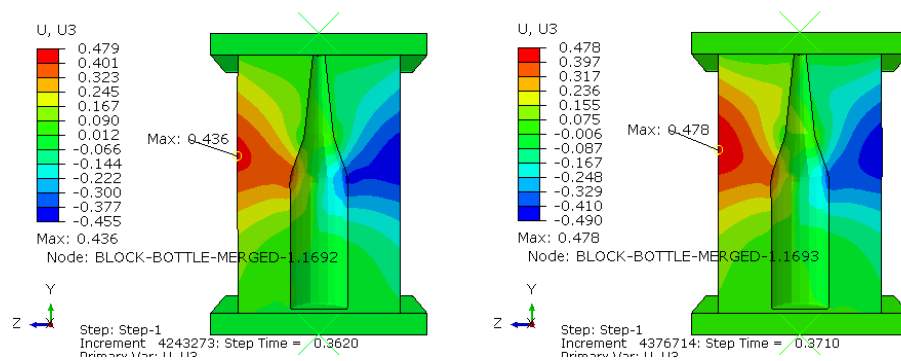


Figure 7.11: GBEB with U3 evolution at the dip

Despite reproducing the dip, the EC32 model retains too much load-bearing capacity in the post-peak regime: beyond the dip, the simulated force remains above the experimental curve. Consequently, the next step is to use EC32 as a baseline and iteratively calibrate its parameters to better reflect the experimental data.

Prior to this, a dedicated section will address the use of symmetry, seeing that each full-block simulation requires up to four days of computation. As shown in Figure 7.7, symmetry was already applied

in the EC37 model to reduce computation time. The constraints this introduces, and their influence on the mechanical response, are analyzed in the following section.

7.5. Influence of symmetry

With computation times of up to four days per full-block simulation, reducing the model to a half (single symmetry plane) or a quarter (two symmetry planes) of the block is an appealing alternative: it reduces the number of degrees of freedom by a factor of two or four (respectively) and shortens the run time accordingly. This section compares the response of the full block with that of the single- and double-symmetry models, and examines whether the symmetry reduction is viable for a problem governed by quasi-brittle fracture.

Force scaling

On a symmetry plane, the displacement component perpendicular to the plane is constrained to zero while the in-plane displacements are allowed. The reaction force that is obtained from the symmetric model therefore represents only the reduced portion of the block. Therefore these forces need to be multiplied by 2 for single-symmetry models, and forces from the quarter model need to be multiplied by 4. This multiplication is done to enable direct comparison between the models. All curves labeled “ $\times 2$ ” and “ $\times 4$ ” in Figures 7.12 and 7.13 have been scaled in this manner.

The reduction by symmetry should be valid if geometry, material, loading and the solution itself are symmetric. The first three conditions are satisfied, with the bottle modeled as a symmetric solid around its axis, the material models being homogeneous, and the platen loading also being symmetric. The fourth condition, however, must to be investigated.

Single symmetry

Figure 7.12 compares the full EC34 model with its single-symmetry variant. Up to the peak, the symmetric half-model response closely follows the full block: the peak load deviates by 2.8%. In the post-peak regime the half model is somewhat more ductile. This artificial gain in capacity is a direct consequence of the constraint imposed by the symmetry. Material on the symmetry plane cannot displace perpendicular to it, so deformation that would cross this plane is suppressed.

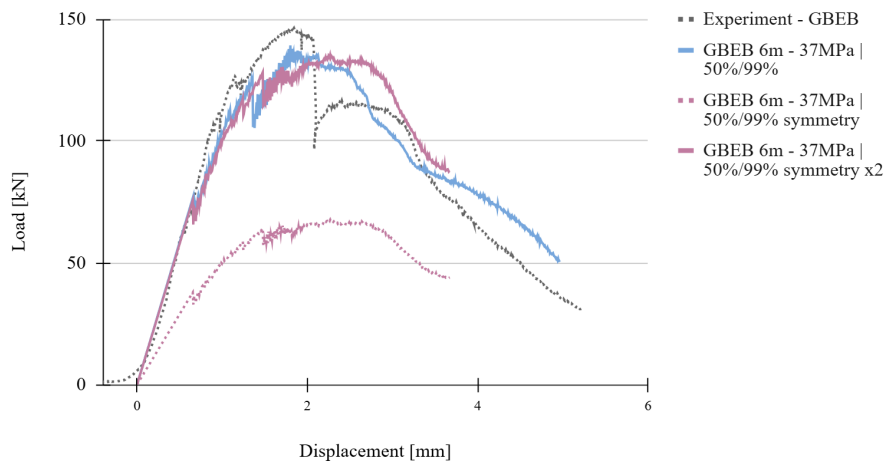


Figure 7.12: Single symmetry of GBEB with EC34

Applying a single symmetry plane reduces the computation time by approximately one day. Given that the deviations in peak load and ductility remain in appropriate proximity to the experimental curve, single symmetry is considered acceptable.

Double symmetry

Figure 7.13 shows the block with material properties EC32 with two symmetry planes. The response is significantly more brittle, and beyond approximately 4 mm the model settles onto a plastic plateau. Figure 7.14 compares the tensile damage evolution of the full block (first row) with the mirrored quarter model (second row). In the latter one, the damaged volume is far larger and propagates much earlier and faster.

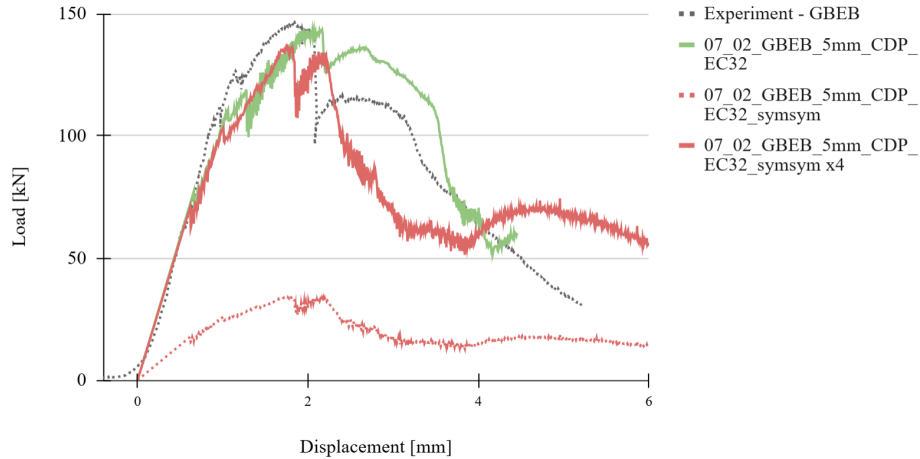


Figure 7.13: Double symmetry of GBEB with EC32

As mentioned before, the displacements perpendicular to the plane are restricted by the symmetry constraint and thus the nodes of the elements can only go sideways or downwards. The symmetric model does not capture progressive fracture accurately, as depicted in figure 7.14. The problem with symmetry is that the numerical solver restricts the solution space to symmetric modes. The solver excludes thus asymmetric modes of cracking. The double symmetric variant is thus not a viable solution.

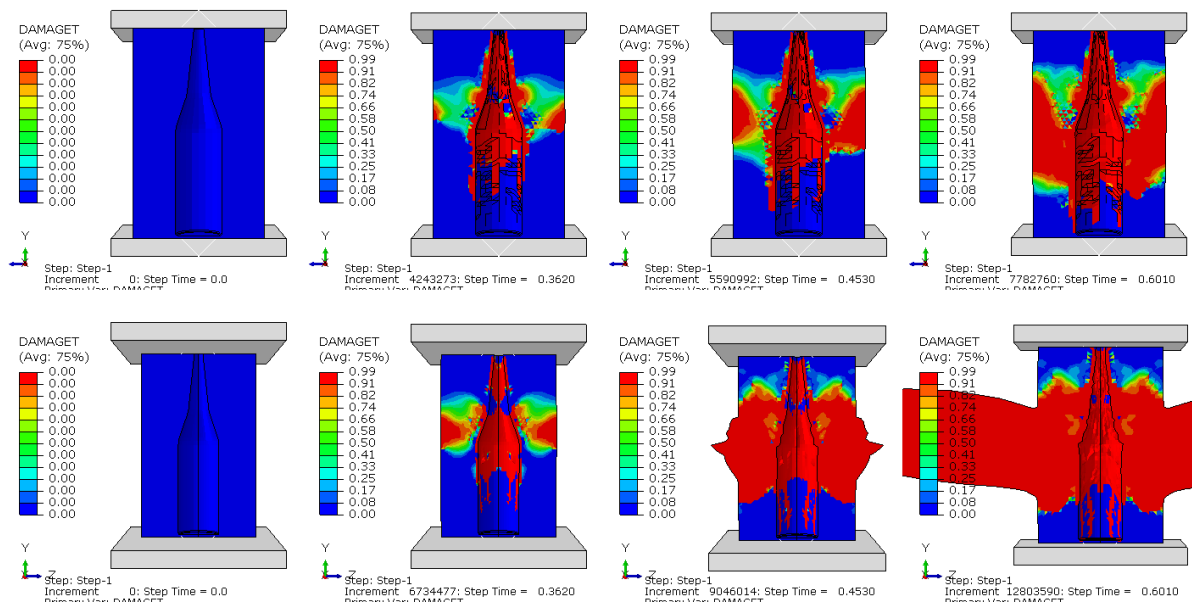


Figure 7.14: Block without symmetry (first row) and block with double symmetry through the middle (1/4th of the block, mirrored)

To reiterate, the single symmetry offers a substantial reduction in computation time at the cost of a modest deviation in the post-peak response. On the other hand, the double symmetry is unsuitable for

use, as its post peak behavior is significantly more brittle and damage is forced to develop in mirrored zones simultaneously. As a result, the damage spreads over more material than in reality.

7.6. Sensitivity of the response to the earthcrete parameters

To gain insight into which material parameters govern which features of the load–displacement response, nine simulations were carried out in which individual parameters of the EC32 baseline were varied one at a time. Because each full-block 5 mm simulation requires up to four days, the analysis was performed on a reduced model: the mesh size was increased from 5 mm to 12 mm and a single symmetry plane was applied (justified in Section 7.5). The purpose of this phase is solely qualitative: to learn the direction of each parameter’s influence, which can be used as a targeted calibration on the full 5 mm model.

Effect of the model reduction itself

Figure 7.14 compares the 5 mm full block with the 12 mm half block under identical earthcrete material properties. The reduced model exhibits an artificially increased load-bearing capacity and a more ductile response. It should be noted that the mesh size and the symmetry reduction were changed simultaneously between the two models in Figure 7.15. From Section 7.5, the single symmetry plane alone accounts for a deviation of 2.8% in peak load. The remainder of the gap in Figure 7.14 is attributable to the mesh coarsening.

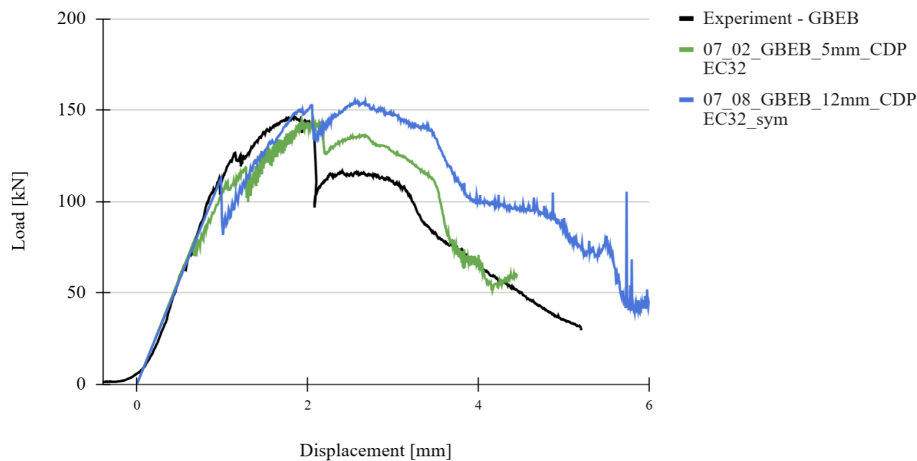


Figure 7.15: Comparison between GBEB 5 mm (whole) and GBEB 12 mm (half symmetry)

Parameter variations

Figure 7.15 shows the nine variations, starting from run 07_08. Table 7.2 lists, for each run, the parameter changed and its effect on the two response features of interest: the peak load and ductility.

The variations of the tensile yield stress (runs 08_05–08_07) demonstrate a clear trade-off between strength and ductility. Lowering σ_t to 3.8 MPa (08_06) causes the largest capacity loss of all runs (139.71 kN) but increases ductility, making the softening branch more gradual. Raising σ_t (08_05, 08_07) leaves the peak essentially unchanged. The response in this case becomes more brittle because of delayed cracking which causes the release of more stored energy at once.

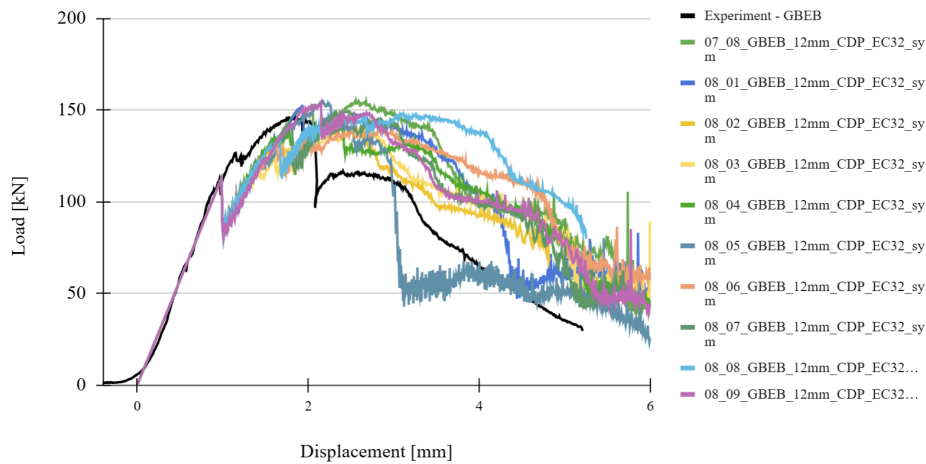


Figure 7.16: Comparison between GBEB 5 mm (whole) and GBEB 12 mm (half symmetry)

Table 7.2: Overview of the nine parameter variations (12 mm mesh, single symmetry). Arrows denote the change relative to run 07_08.

Run	Parameter changed	Change [$\uparrow/\downarrow$]	Peak load [$\pm$]	Peak load value [kN]	Ductility [$\pm$]
07_08	baseline (EC32)	(–)	(–)	155.17	(–)
08_01	Tensile Damage	99% $\uparrow$	–	152.18	–
08_02	Sigma_c	4.86 MPa $\downarrow$	–	144.35	–
08_03	Sigma_c	5.03 MPa $\downarrow$	–	140.29	–
08_04	Inelastic strain_c	0.09 $\downarrow$	–	140.26	+
08_05	Tensile yield stress	4.2 $\uparrow$	–	154.51	–
08_06	Tensile yield stress	3.8 $\downarrow$	–	139.71	+
08_07	Tensile yield stress	4.1 $\uparrow$	–	149.21	–
08_08	Dilation angle	34 $\uparrow$	–	148.02	+
08_09	Sigma_c	5.06 $\uparrow$	–	153.45	–

Reducing the compressive strength (runs 08_02, 08_03) lowers the peak load (144.35 and 140.29 kN) without any gain in ductility. This behavior is to be expected as crushing is itself a brittle mechanism. Thus, decreasing this value reduces capacity and ductility simultaneously. Increasing σ_c (08_09) does not raise the peak (153.45 kN). This suggests that the capacity is limited by the tensile failure rather than by compressive strength.

The compressive softening strain (08_04) and the dilation angle (08_08) both trade capacity for ductility. Reducing the inelastic strain triggers crushing earlier, lowering the peak to 140.26 kN and flattening the descent. Increasing the dilation angle to 34° causes more plastic volumetric expansion.

Increasing the tensile damage variable (08_01) from 93% to 99% barely affects the peak (152.18 kN) but reduces ductility. This is expected: the damage variable causes the stiffness degradation and thus accelerates the post-peak stiffness loss.

Overall, the results are consistent. Ductility increases almost exclusively in the runs where the peak load drops the furthest (08_04, 08_06, 08_08), reflecting that a lower peak implies less stored elastic energy to be released during the inelastic phase.

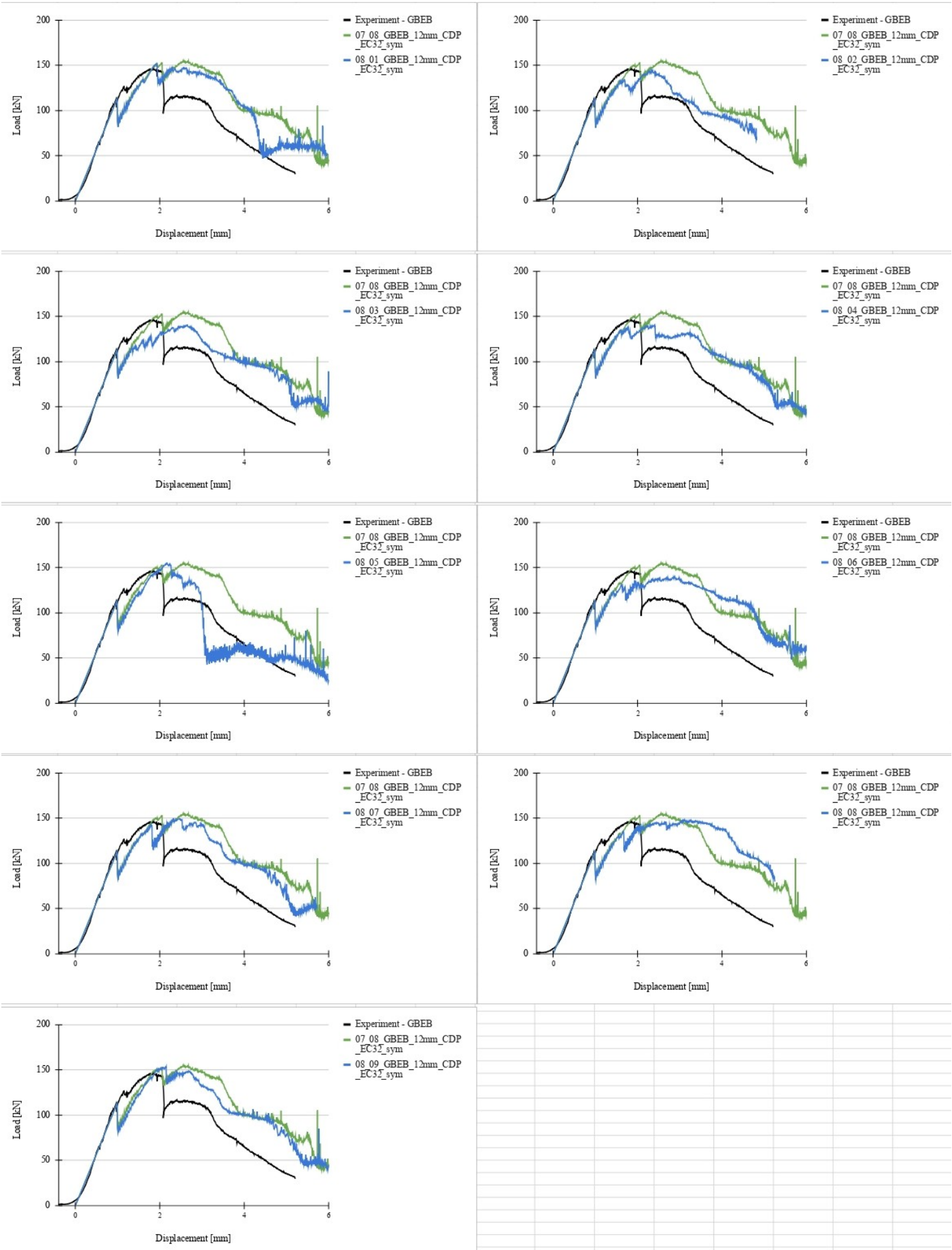


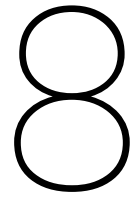
Figure 7.17: Earthcrete parameter variations (see Appendix J for details)

7.7. Strength and debonding energy of the interface

The interaction between glass and a cementitious matrix can be described by a cohesive zone model, in which the interface is governed by a traction–separation law. Traction refers to the stress on the surface, expressed by force per unit area across the interface (MPa). This law states that the interface behaves elastically until a bond strength is reached. After this point the traction decreases with increasing separation until the surfaces are fully debonded. The area under this curve is the debonding (fracture) energy. Two parameters characterize the interface: the bond strength, which controls when debonding initiates, and the debonding energy, which controls how much energy is required to fully debond the surfaces.

The only available experimental reference for a glass–cementitious interface is the work of Gilabert et al. [19], who report a bond strength of 0.96 N/mm^2 and a debonding energy of 0.11 J/m^2 . Both values are very low: debonding initiates below 1 MPa and consumes almost no energy, and the bond fails in a nearly brittle manner. Two limitations apply to the transfer of these values to the present case. They were obtained on borosilicate rather than soda-lime glass, and commercial bottles additionally carry a polyethylene cold-end coating (Section 3.2) that is specifically designed to reduce surface friction and can be expected to lower the bond further. The interface is thus the least characterized component of the composite block.

The traction–separation law requires an unmerged geometry with contact definitions along the entire bottle surface. A cohesive interface model with these values was implemented in one exploratory simulation, in appendix H. The CZM reduced the peak capacity relative to the merged model and shifted the bottle damage toward the neck and heel.



II. Numerical analysis of different CGBEB configurations

This chapter presents the numerical results of the CGBEBs (Cubic Glass Bottle Earthcrete Brick). First, the design types are presented. Then the calibration of the glass material model is described to account for the sensitivity of the mesh. The model is then validated using different time increments. The mechanical behavior of the blocks is evaluated by analyzing force-displacement curves and by comparing the different block configurations. Detailed analysis of tensile damage, equivalent plastic strain (PEEQ), stress distributions, and displacements provide insight into the failure mechanisms. The chapter investigates the effects of varying concrete cover, inter-bottle spacing, and the number of embedded containers within the block. Finally, the effects of direct bottle-to-bottle contact is investigated.

8.1. Design types

To ensure consistent comparison between design configurations, each block should share identical outer dimensions. Based on wall thickness estimates from reference projects described in Chapter I.3, a uniform block thickness of 24 cm was adopted. In the reference photos, it is unclear whether the bottles share a height similar to those described in the previous chapters, as bottle sizes vary from country to country. Nevertheless, a 24 cm depth should provide a suitable dimension for constructing multi-story walls.

A thickness of 24 cm also ensures that the top and bottom surfaces of each embedded bottle align with the outer faces of the earthcrete block. Although less critical for vertically oriented blocks, it allows for the option of rotating the blocks horizontally in future research. This alignment is functionally advantageous for horizontally oriented blocks as light can pass through the bottles across the wall thickness, a feature observed in most reference projects. Due to time limitations, all simulations and experiments were performed using vertically oriented bottles. The selected block dimensions can accommodate multiple bottles while remaining below the 20 kg maximum operable weight for manual handling. Since the block types contain different numbers of bottles, their weights vary accordingly.

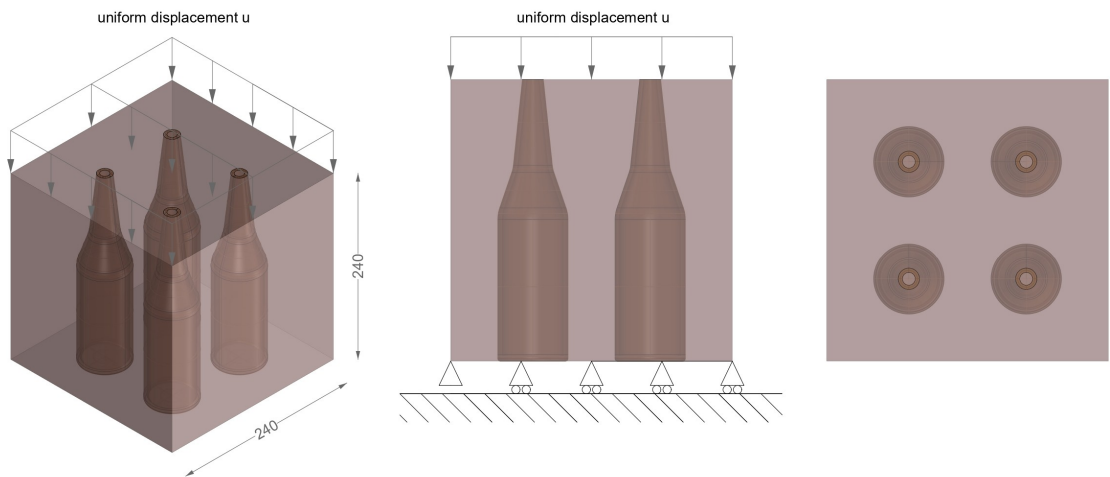


Figure 8.1: Cubic GBEB geometry and boundary conditions

The initial design comprised six block types: B1, B2, B3, B4, B5 and B9. The types differ primarily in the number of bottles (B1 block with 1 bottle, B2 block with 2 bottles, etc.). Within each type, there are subtypes that differ in earthcrete cover thickness (defined as the distance from the outer surface of the block to the outer surface of the bottle) and inter-bottle spacing, with the two variables being dependent on each other.

A sixth block type was added with an arrangement of nine bottles (B9) to investigate the effects of maximizing the number of bottles per block. The original concept is illustrated below with a total of 15 configurations.

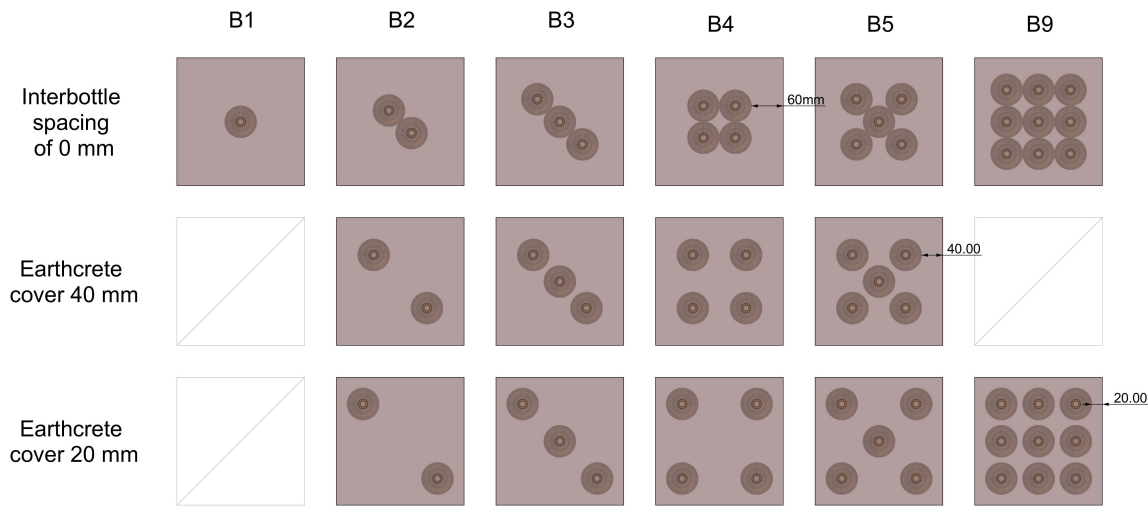


Figure 8.2: Initial design types and configurations

As shown in the figure, the CGBEB type B1 has only one variant. This is because the earthcrete cover for this type can only be adjusted by shifting the bottle asymmetrically relative to the outer surface of the block. Consequently, decreasing the earthcrete cover on one side automatically increases it on the opposite side. For this reason, additional variants were not pursued. For type B9 (nine-bottle configuration), testing with an earthcrete cover of 4 cm was not possible due to space constraints as the bottles occupy too much of the block’s volume. Only a 2 cm earthcrete cover could be realized.

Because these models are computationally expensive, only a subset was selected for numerical testing. Ten out of the total configurations have been chosen for simulation, as depicted in Figure 8.3. The selection criteria allows systematic comparison across the following variants: B1 through B5 (+B9) (with a constant 4 cm earthcrete cover), B4 with three varying cover thicknesses, and B5 with two varying cover thicknesses. Once the numerical analysis is complete, the results will be evaluated to identify the configuration with the best performance, which will then be tested experimentally for validation.

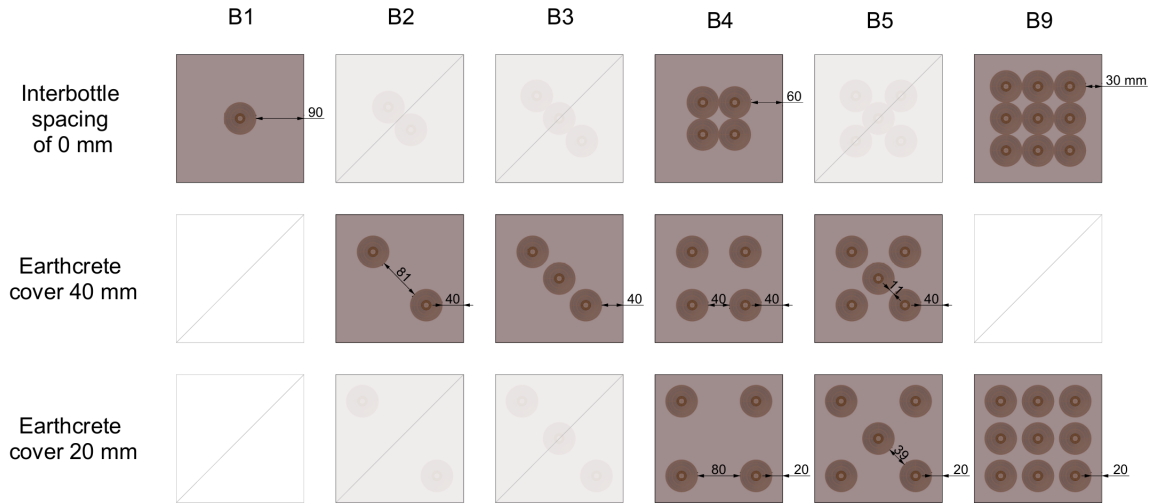


Figure 8.3: Selected design types and configurations

8.2. Material model calibration for mesh sensitivity

In previous stages of this research, mesh sizes of 5 mm and 12 mm were mostly used. The computational cost associated with the 5 mm mesh was higher than previously anticipated. As a result, for the subsequent sections and chapters, the mesh size is increased to 10 mm.

In explicit Abaqus, altering the mesh size influences the predicted failure point of the glass. To account for this, the tensile yield stress for the same bottle model was calibrated to match the average fracture load obtained from experimental data. The iterative adjustments made during this calibration are presented in graphical form and the final iteration is presented in tabular form.

The closest fit with the experimental average was achieved in the final iteration, corresponding to model 10_05_Bottle_10mm_CDP_26MPa.

Material properties	Glass Tensile Behaviour		Glass Tension Damage	
	σ_t (MPa)	ε_{cr}	d_t	ε_{pl}
10_05_Bottle_10mm_CDP_26MPa_05	26	0	0	0
	0.26	5.90×10^{-4}	0.99	2.00×10^{-5}

Table 8.1: Glass material properties for mesh size 10 mm.

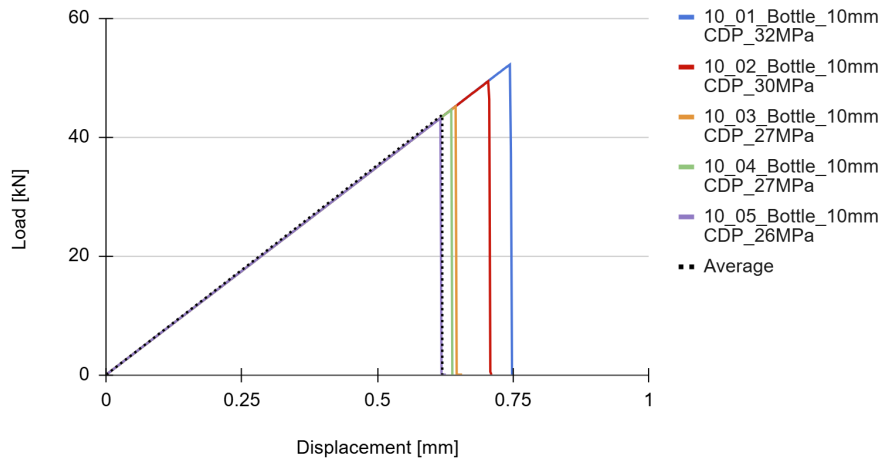


Figure 8.4: Iterative calibration of tensile yield stress for a 10 mm mesh model based on experimental fracture loads of glass bottles.

Model 10_03 and 10_04 differ in the cracking strain values used: 8.40×10^{-4} and 6.10×10^{-4} respectively, while maintaining the same tensile yield stress. The lower cracking strain corresponds to a slightly lower fracture load, as expected, though the difference is not significant.

The following material properties for earthcrete have been used for the blocks, calibrated by Hoessein Alkisaiei:

Material properties	Earthcrete Tension Behaviour		Earthcrete Tension Damage	
	σ_t (MPa)	ε_{ck}	d_t	ε_{pl}
Earthcrete	8.28	0	0	0
	0.0828	0.0071	0.99	0.0071
Earthcrete Compression Behaviour and Damage				
	σ_c (MPa)	ε_{in}	d_c	ε_{pl}
	5.8	0	0	0
	8	0.0034	0.0034	0.0034
	7	0.0074	0.00657	0.0074
	5	0.0124	0.0099	0.0124
	2	0.0204	0.0154	0.0204
	0.6	0.0284	0.0284	0.0284

Table 8.2: Earthcrete tension and compression properties for mesh size 10 mm.

8.2.1. Validation of the model through time increments

One of the challenges of using explicit solvers in Abaqus concerns the accuracy of the solution in nonlinear problems. During a time step, small errors can arise at strong nonlinearities, and these errors may accumulate over time, leading to substantial inaccuracies in the final solution. Abaqus does not automatically correct these errors [13]. Abaqus can, however, adapt the time increment size to maintain stability. To obtain a stable solution at $t + dt$, the time increment must be very small as discussed in subchapter 5.1.1. Alternatively, a fixed time increment can be defined by the user. In most cases, the automatic time increment option performs well and is generally the recommended option by the ReaseachGate community [51].

The limits for the time increment can be specified in the step module. When the stable time increment is decreased slightly from a variable value of approximately 3.335×10^{-8} to 1×10^{-8} , the mechanical

behavior changes significantly, as depicted in Figure 8.5.

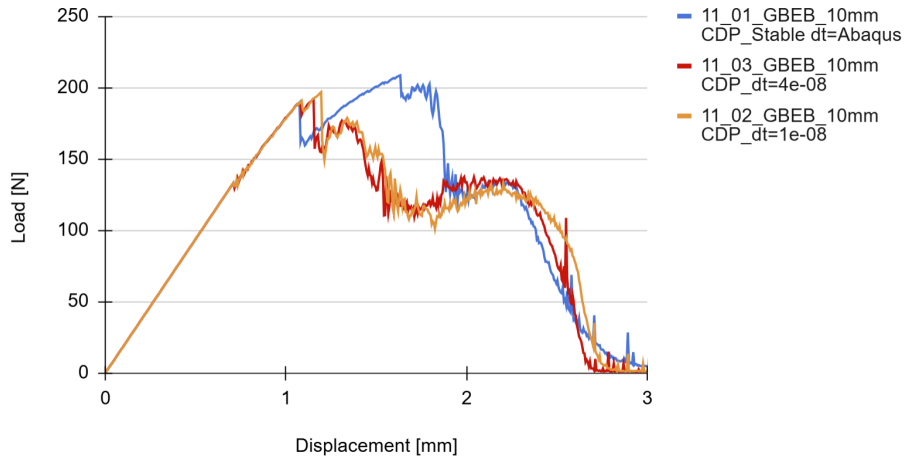


Figure 8.5: Validation of the model through changes in length of the time increment.

If a smaller time increment is imposed, the theoretical stability limit is violated. Thus the model cannot be validated through this method.

If a larger time increment is imposed, the central difference scheme violates its conditional stability limit, leading to numerical instability which in turn may cause the model to behave erratically. The theoretical stability limit must abide by the following equations:

$$\Delta t_{\text{stable}} = \frac{L^e}{c_d} \quad \text{where} \quad c_d = \sqrt{\frac{E}{\rho}}$$

When increasing the stable time increment, Abaqus aborts the simulation and gives the following error: "The ratio of deformation speed to wave speed exceeds 1.0000 in at least one element". This implies that the imposed time increment violates the inequality $\Delta t \leq \Delta t_{\text{stable}} = L^e/c_d$; consequently, the computed deformation speed locally exceeds the physical dilatational wave speed $c_d = \sqrt{E/\rho}$.

Moreover, by changing the frequency at which output is specified, the mechanical behavior is also changed, as can be visualized in the figure below. When jumping from 0.001 dt to 0.01 s, the curve follows the behavior well, but when this is increased to 0.05 s, the graph shows that the capacity is increased, when in reality it should be taking the data points on the line. The reason why this is, is still unknown.

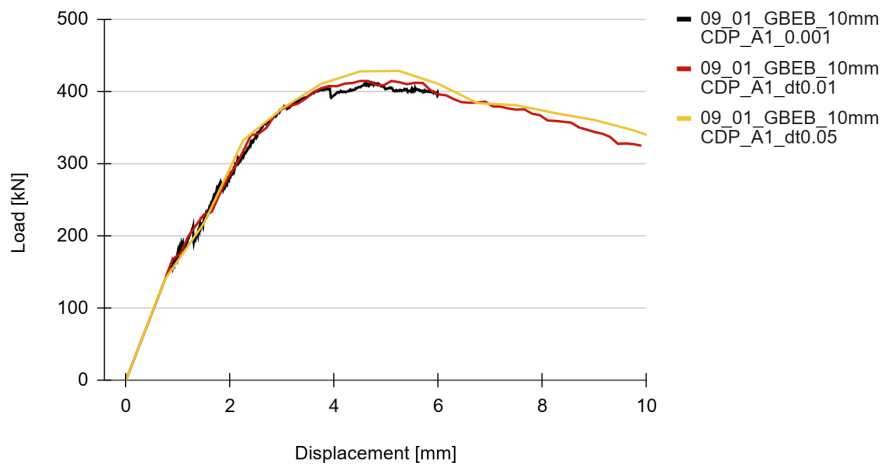


Figure 8.6: Validation of the model through changes in length of the time increment.

8.3. Numerical results of the CGBEBs

The force-displacement graphs of the cubic blocks can be visualized in the figure below.

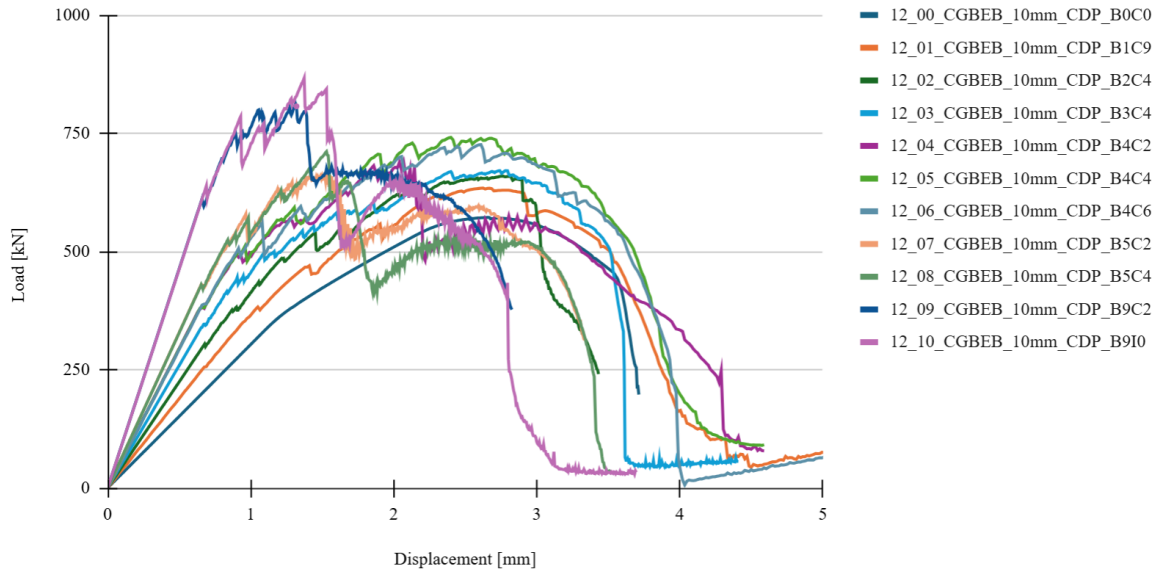


Figure 8.7: Force-displacement of the Cubic GBEB configurations

As can be seen, the blocks behave differently across the configurations. In the following subsections, the different types will be analyzed and compared.

8.4. Influence of concrete cover and inter-bottle spacing

To begin with, the influence inter-bottle spacing and earthcrete cover will be analyzed. The blocks of type B4 display an initial elastic region up to a step time of 0.064 s and displacement of 0.945 mm. From the force-displacement graph of block type B4, it can be seen that variant B4C2 (block with 4 Bottles and earthcrete Cover of 2 cm) has a lower load capacity than the other two variants, exhibiting a significant dip between 2.055 mm and 2.220 mm of displacement.

All three variants shown in figure 8.8 share the same initial elastic stiffness. Blocks with earthcrete covers of 4 cm (B4C4) and 6 cm (B4C6) show similar performance, although the block with 6 cm has a slightly lower load capacity compared to the one with 4 cm earthcrete cover.

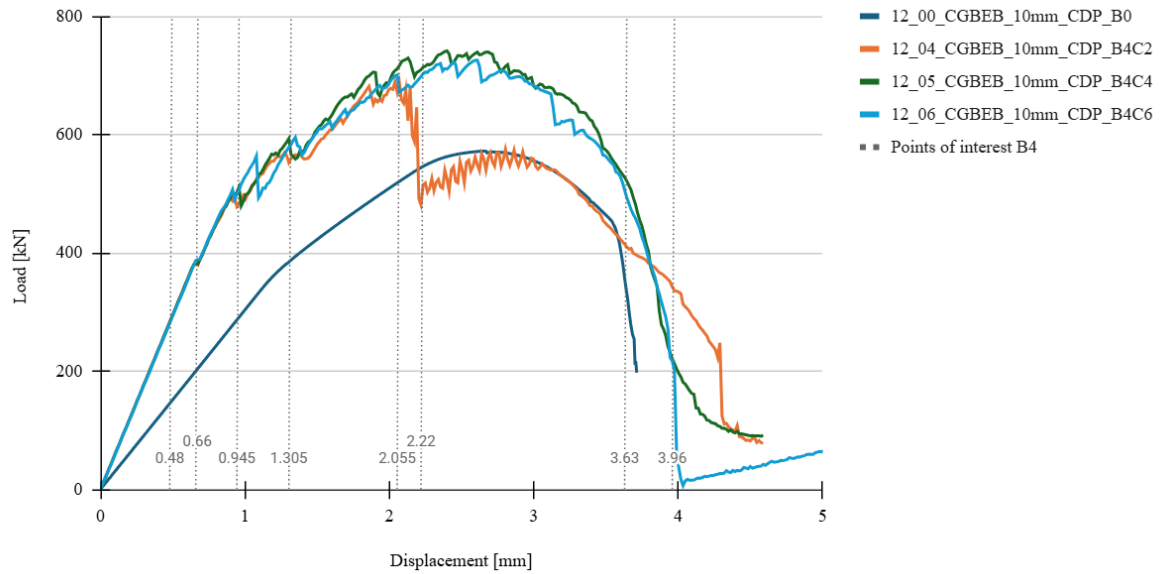


Figure 8.8: Force-displacement of the CGBEB type B4

Figure 8.10 captures eight representative moments on the force-displacement graph, where tensile damage can be observed to spread progressively. Within the elastic region, the glass begins to break at the shoulder region. Zooming in, at a step time of 0.064 seconds and displacement 0.945 mm, tensile damage begins to affect the earthcrete matrix around the bottle, propagating mainly around the shoulder of the bottle. This phase also marks the transition into the crack propagation phase inside the earthcrete matrix i.e., the inelastic phase.

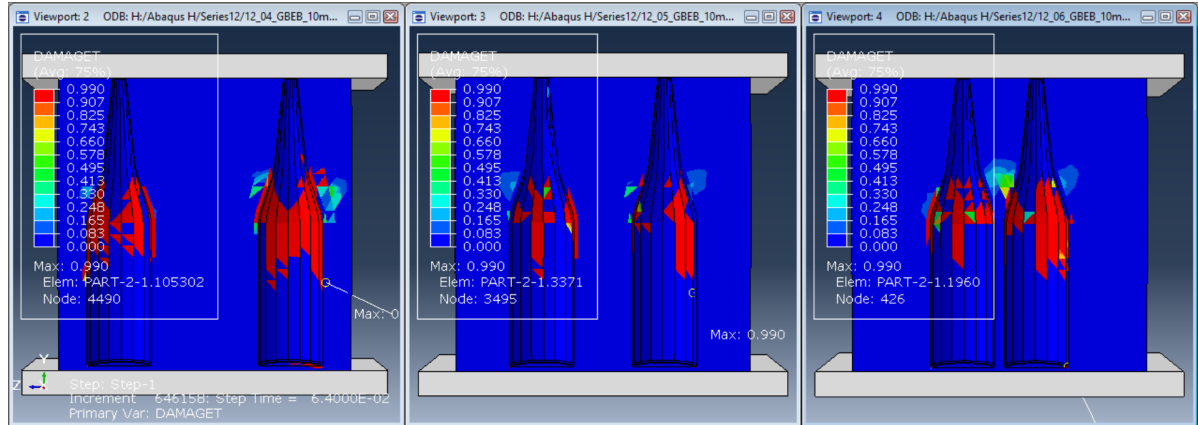


Figure 8.9: Affected area after glass breakage CGBEB type B4 at time step 0.064 s and displacement of 0.945 mm

Interestingly, the bottle fails at higher principal stresses than if the bottle is embedded in the matrix. This is discussed further in appendix E.

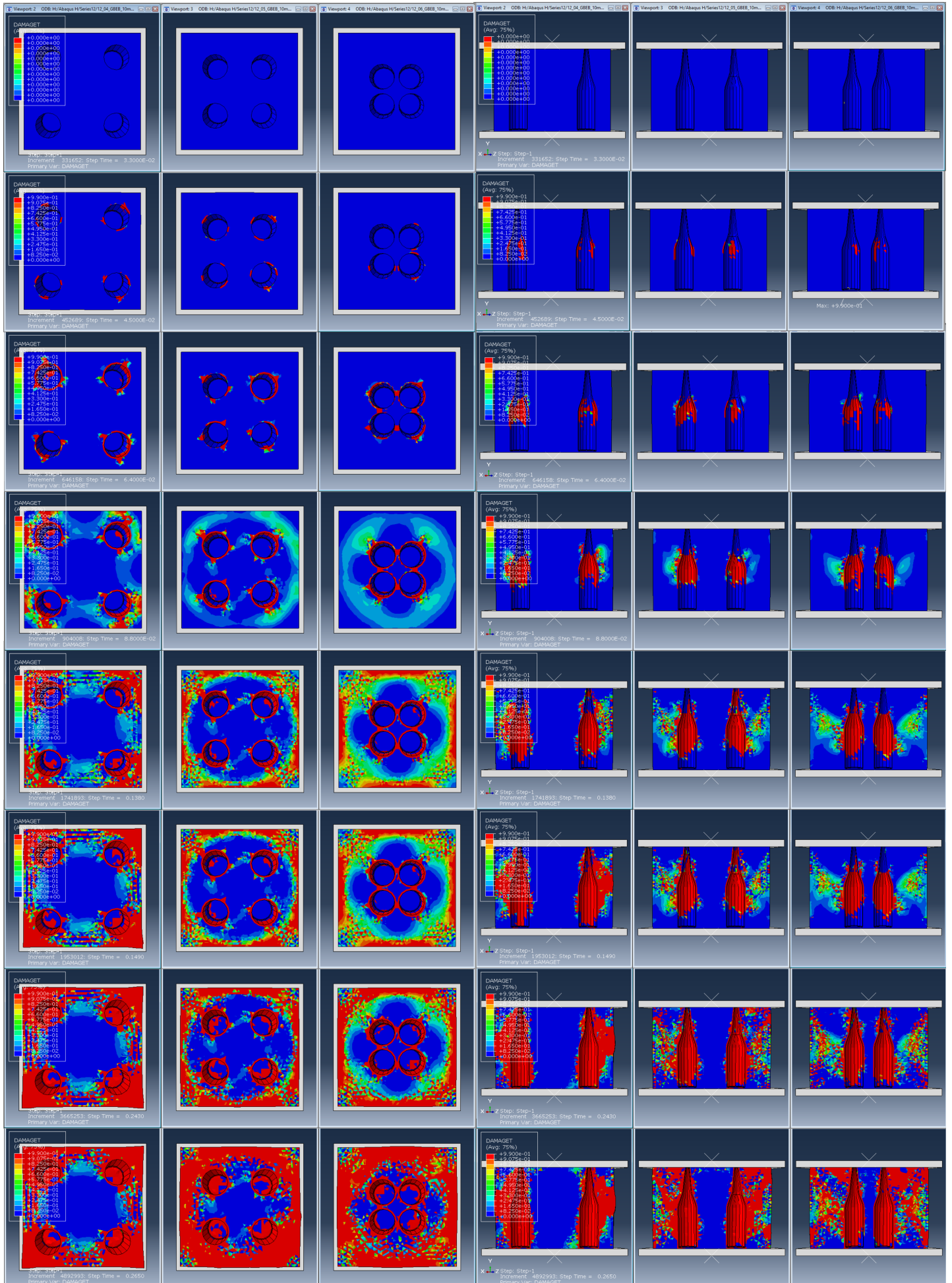


Figure 8.10: DAMAGE of CGBEB type B4 (horizontal cross-section at shoulder height (left) and vertical cross-section diagonally of the block, through the bottles (right))

In type B4C2 (left), damage is concentrated at the corners of the block, while for the other two types, tensile damage is more evenly distributed across the surface of the cubes. Throughout the numerical simulation, the central region of the block between the bottles remains undamaged in this cross-section. This may be explained by the confining effect of the glass in the middle, combined with the fact that the block is under compression, whereas tension occurs predominantly at the edges. Although a significant dip is observed for B4C2 in Figure 8.8 at 2.22 mm, the tensile damage figures reveal no major affected areas. There is only a slight increase in the damaged area, which further connects the damaged corners of the block.

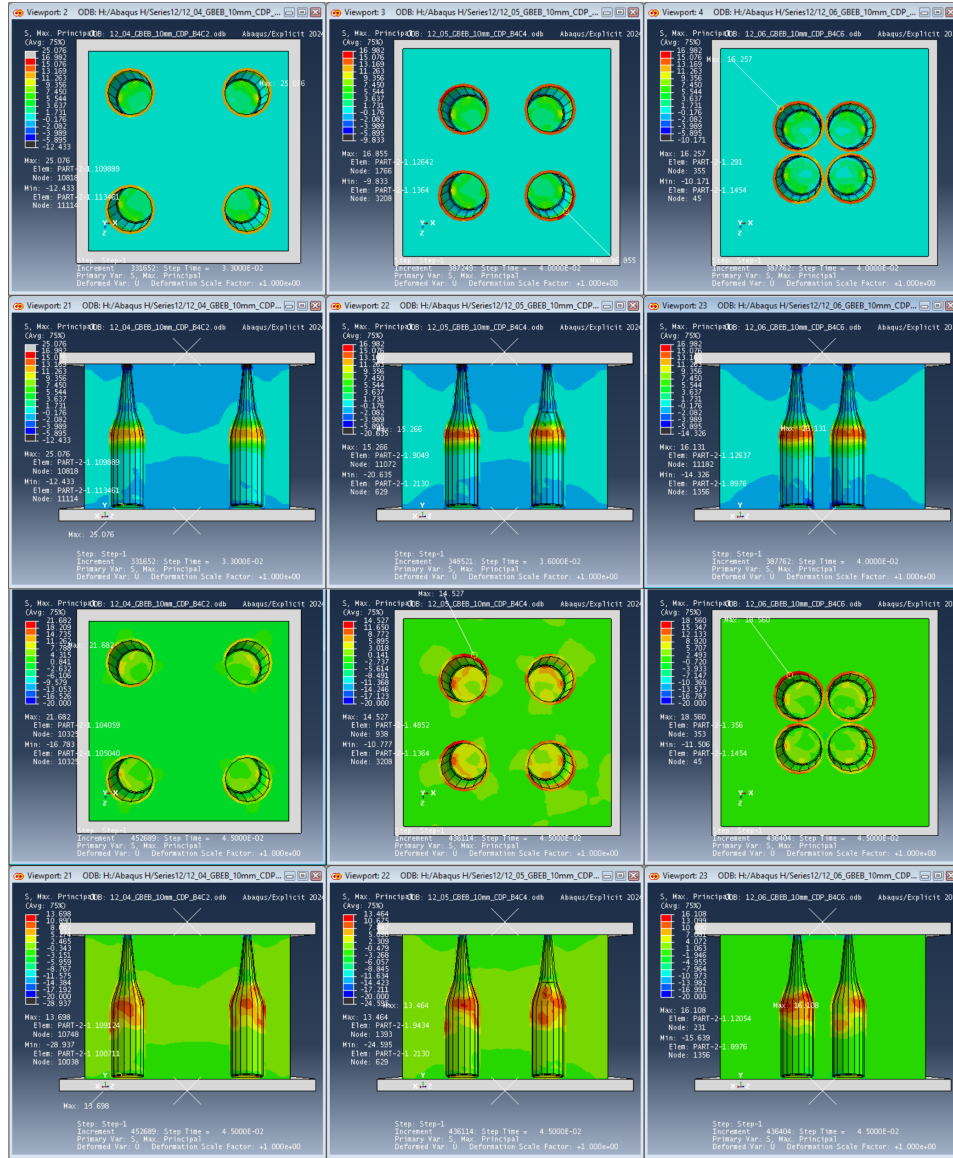


Figure 8.11: Captured principal stresses (P1) before damage tension in the glass (upper figures) and after significant tension damage of the glass (below)

The maximum principal stress range from 14.50 MPa to 15.64 MPa, before any tensile damage occurs in the glass. At the shoulder height of block B4C2, the maximum principal stress is 14.593 MPa. In the left figures, the stress at the base of the bottle is higher, reaching 25.076 MPa. This is likely due to the placement of the bottle, as the deflection caused by the loading plate pushes the material on the outside away from the center. This phenomenon is known as *barreling*, which occurs because the top and bottom faces are constrained by friction, while the middle section is free to expand outward.

Barreling is more pronounced in this block type because the glass units are located closest to the outer surfaces and thus is affected by higher lateral forces.

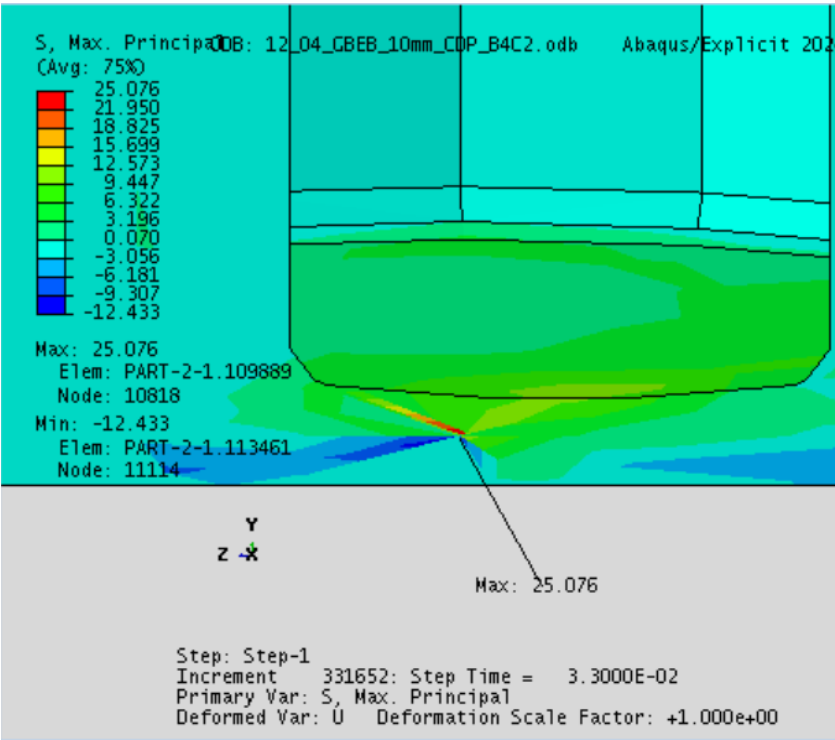


Figure 8.12: High stresses of CGBEB type B4C2 at the base area of the bottle

After a certain point, the maximum principal stresses in the glass become irrelevant as damage tension spreads throughout the glass, as depicted in figure 8.11.

8.5. Influence of number of bottles on the performance of CGBEBs

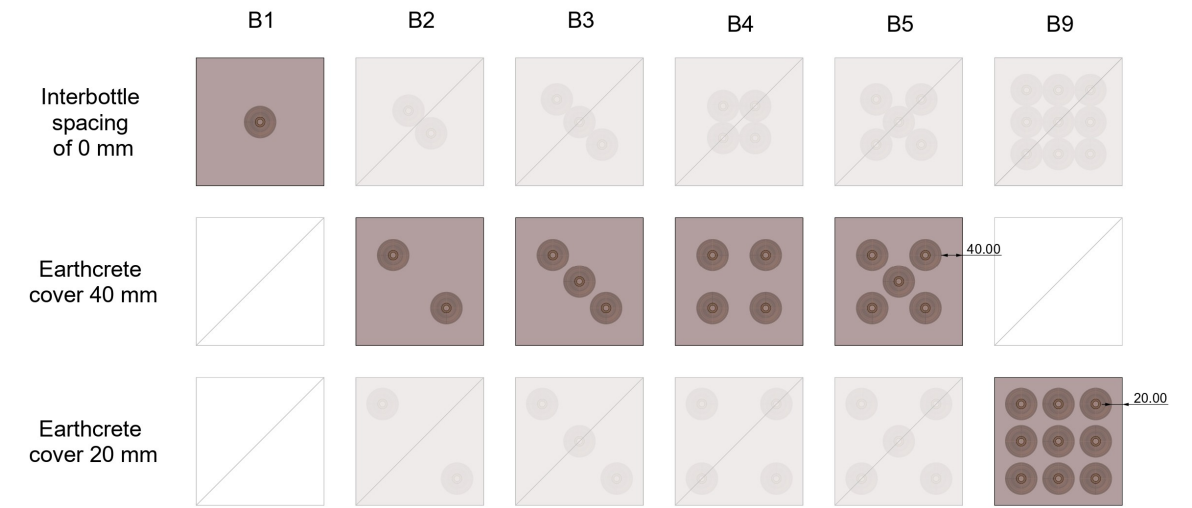


Figure 8.13: CGBEB types B1, B2, B3, B4, B5 and B9

To determine the capacity of blocks with varying numbers of bottles, seven different block types were numerically tested using Abaqus: B0, B1, B2, B3, B4, B5, and B9. All blocks display an initial elastic region up to a displacement of approximately 0.945 mm. Clearly, block type B9C2 achieved the highest peak force at 806.92 kN. After this peak, the block loses some capacity, exhibiting a smaller plastic region than the other types.

When comparing blocks B0 through B5 against each other, it can be noted that the best-performing block is B4C4. This is quite surprising, as a higher number of bottles in other cases typically indicated higher capacity. However, for block B5C4, a dip in capacity is observed at 1.53 mm displacement, reaching 711.23 kN. This type exhibits a more brittle behavior, followed then by a smaller plastic region.

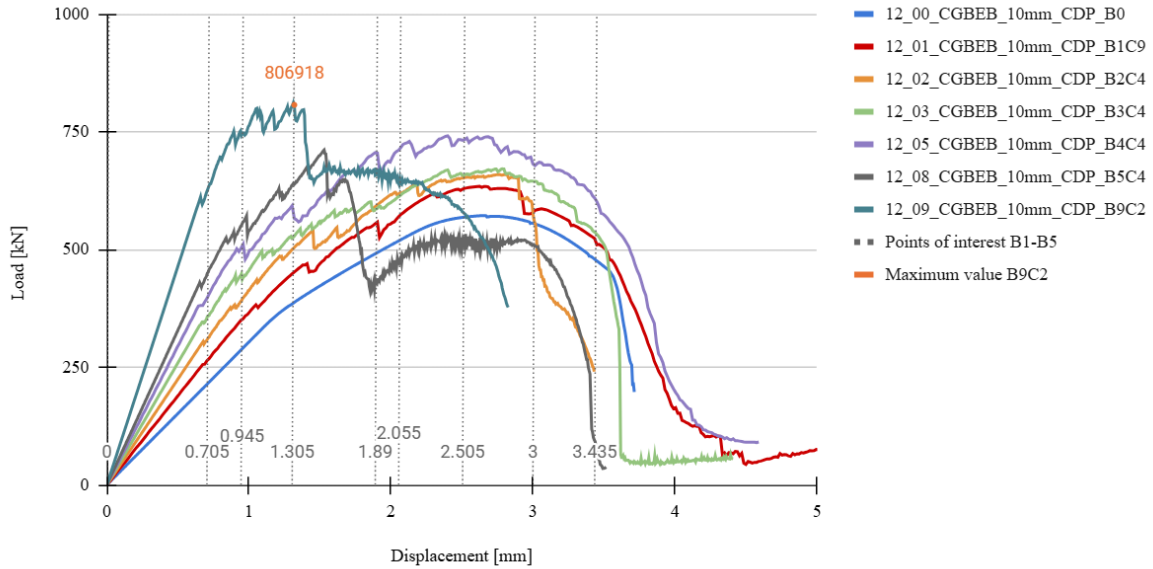


Figure 8.14: Force-displacement graph of CGBEB types B1, B2, B3, B4 and B5

By increasing the number of bottles, the units acquire an increasing axial stiffness. This coincides with what was observed numerically as the bottle count increased as depicted in figure 8.15. Axial stiffness is defined as the resistance to axial deformation under tension or compression. Mathematically it is defined as:

$$K = \frac{AE}{L}$$

where:

A = cross-sectional area

E = elastic modulus

L = length

AE = axial rigidity

For a block containing multiple bottles, the force-displacement relationship follows Hooke's law:

$$F = K \cdot u$$

where F is the applied force and u is the displacement. The total axial stiffness of the block can also be expressed as the sum of the individual stiffness of the bottle:

$$K = n \cdot k_{\text{bottle}}$$

where n is the number of bottles and k_{bottle} is the individual bottle stiffness.

Combining these relationships, the full system can be described as:

$$\begin{cases} K = \frac{AE}{L} \\ K = n \cdot k_{\text{bottle}} \\ F = K \cdot u \end{cases}$$

Thus, the applied force can be directly related to the number of bottles:

$$F = n \cdot k_{\text{bottle}} \cdot u$$

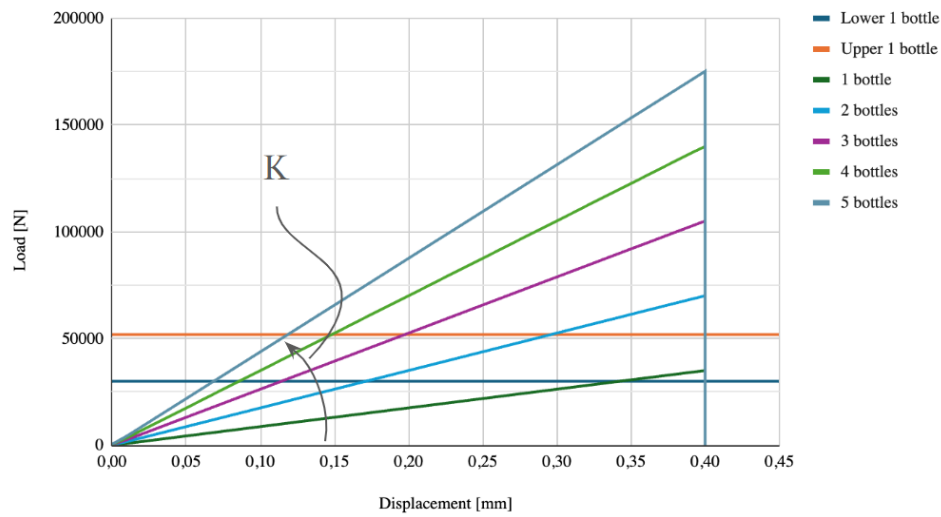


Figure 8.15: Amount of bottles ($t=2.5$ mm, Mesh size 10 mm)
[4]

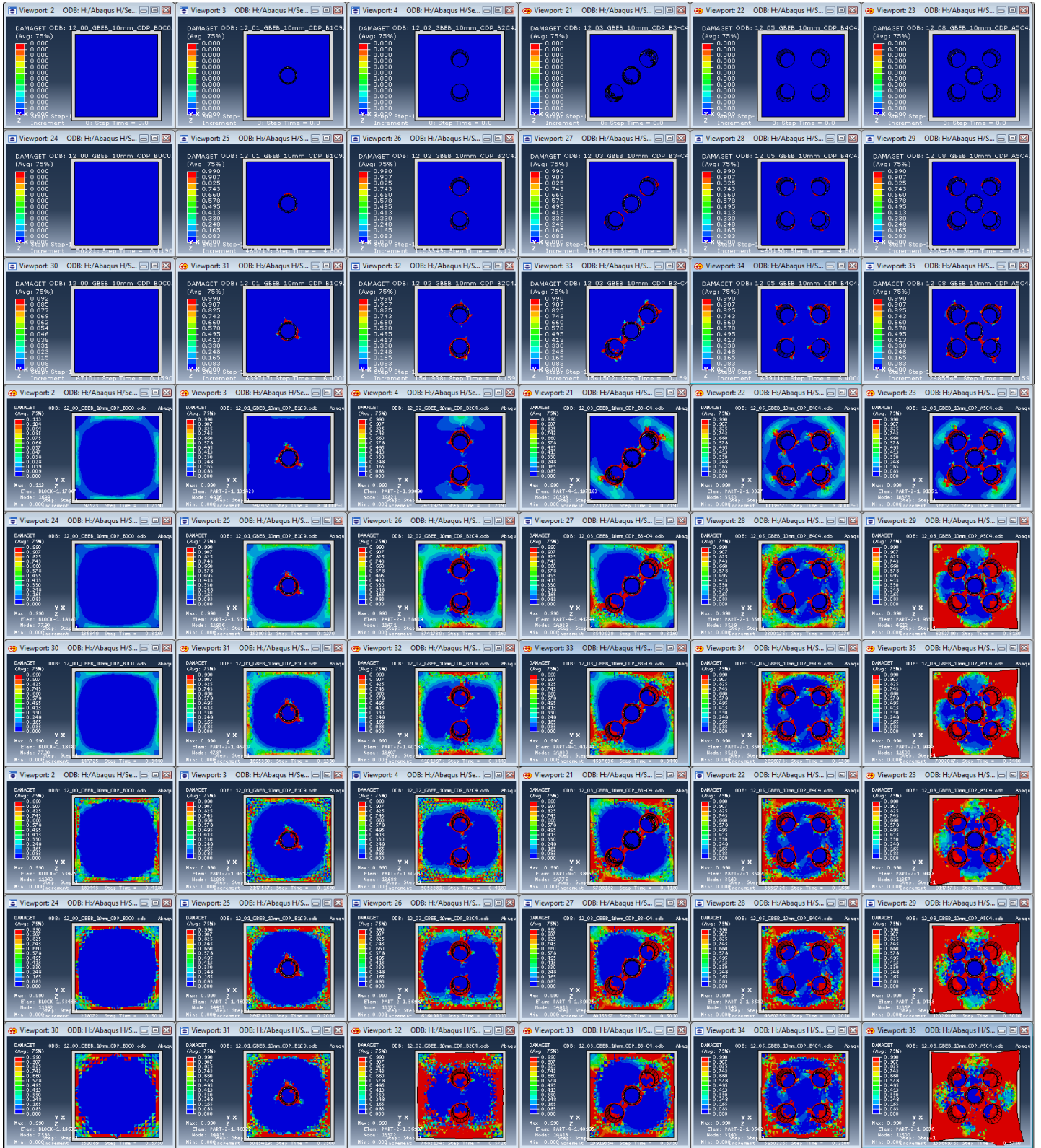


Figure 8.16: DAMAGET of CGBEB type B1, B2, B3, B4 and B5 respectively (horizontal cross-section at shoulder height)

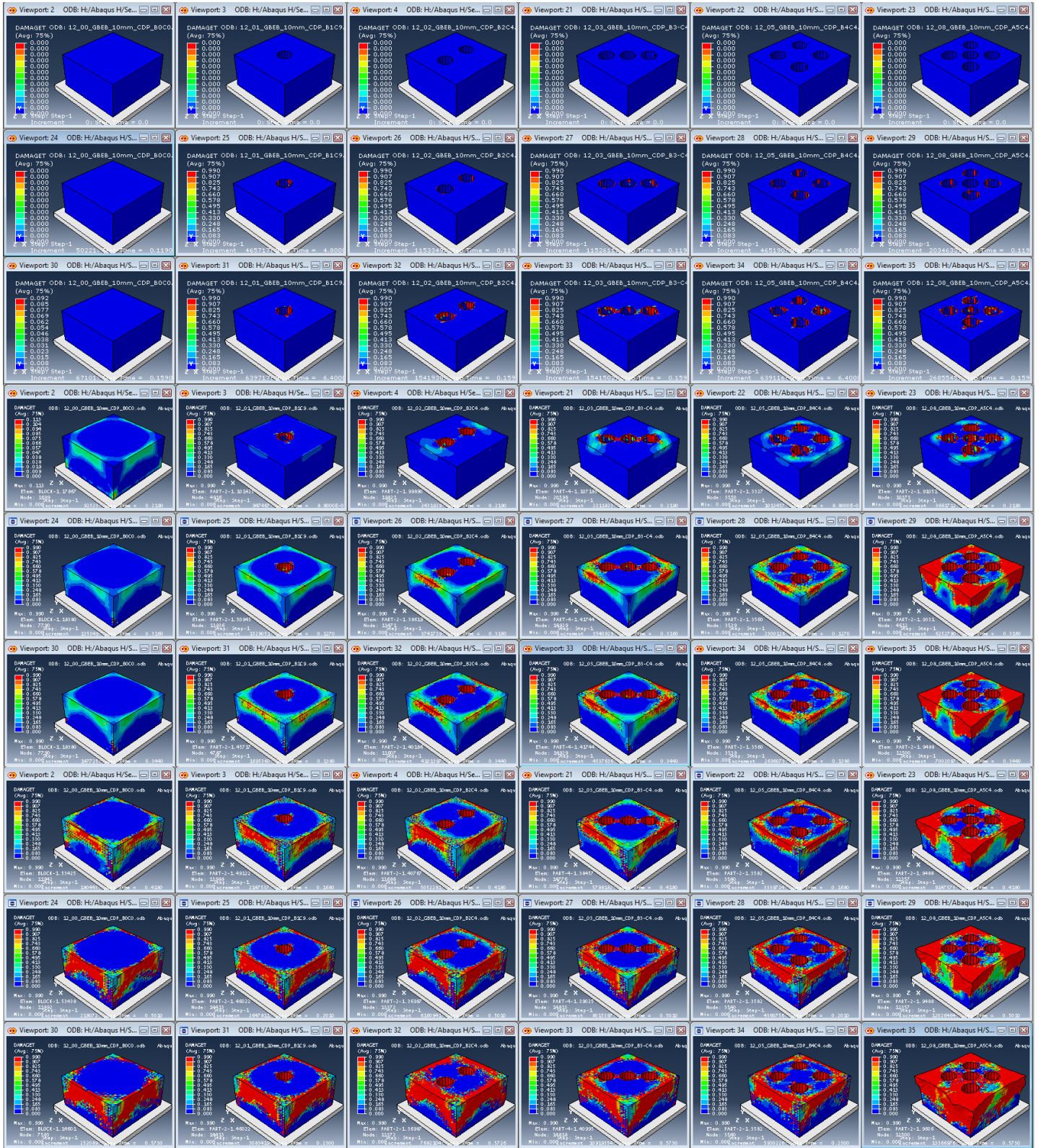


Figure 8.17: DAMAGET of CGBEB type B1, B2, B3, B4 and B5 respectively (3D view with horizontal cross-section at shoulder height)

Figures 8.17 and 8.16 capture nine representative moments on the force-displacement graph, where tensile damage can be observed to spread progressively. Within the elastic region, the glass begins to

break in the shoulder region (represented by the first 3 rows of images). Then, as mentioned before, the tensile damage begins to affect the earthcrete matrix around the bottle, propagating mainly around the shoulder of the bottle. The last column of figures (B5C4) show an increased area of damage, mainly at the corners of the block in the middle.

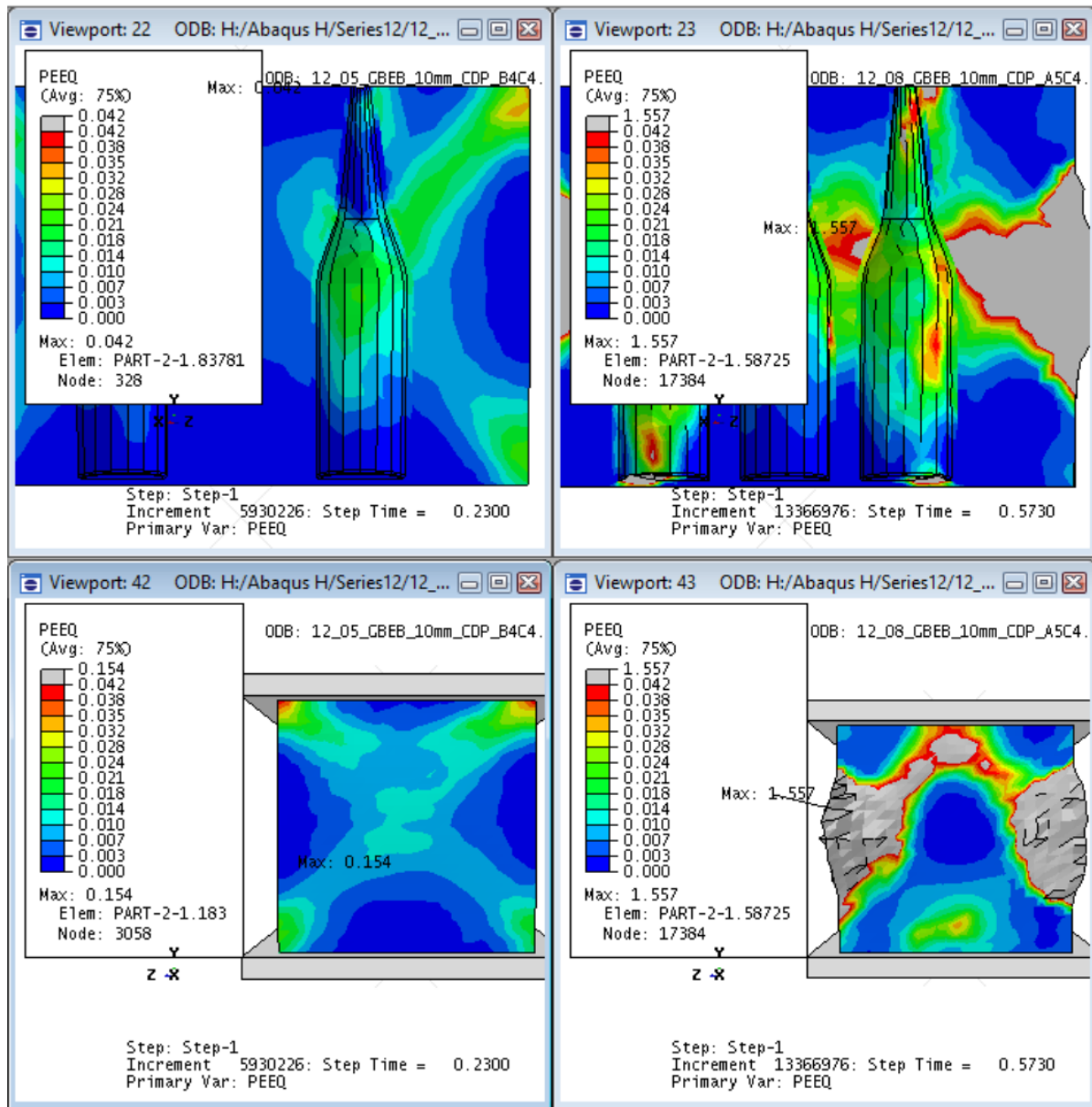


Figure 8.18: Comparison of PEEQ of the CGBEB type B4 and type B5 (vertical cross-section diagonally through the block)

To understand this behavior, PEEQ is analysed, as it provides insight into identifying areas susceptible to fracture. It is a non-negative scalar quantity. If a contour plot of PEEQ shows a value greater than zero, it indicates that part of the model has undergone plastic (non-linear) deformation. In the figure above, an upper boundary was specified to allow comparison between block B4C4 and B5C4 at a PEEQ value of 0.042, corresponding to 4.2% plastic strain.

While the deformation in B4C4 follows a crisscross pattern in the vertical cross-section as well as at the outer Z-Y elevation, in B5C4, the majority of plastic strains and deformations occur along the middle vertical outer edges of the block and between the bottles themselves. This is likely because the three bottles are aligned and positioned closely together, causing damage to propagate in a linear fashion. The damage propagation occurs in a completely different manner compared to the other cases. From

an experimental perspective, this would manifest as the earthcrete corners falling off the block. The areas affected by the load for all the blocks in this series is shown in Figure 8.19.

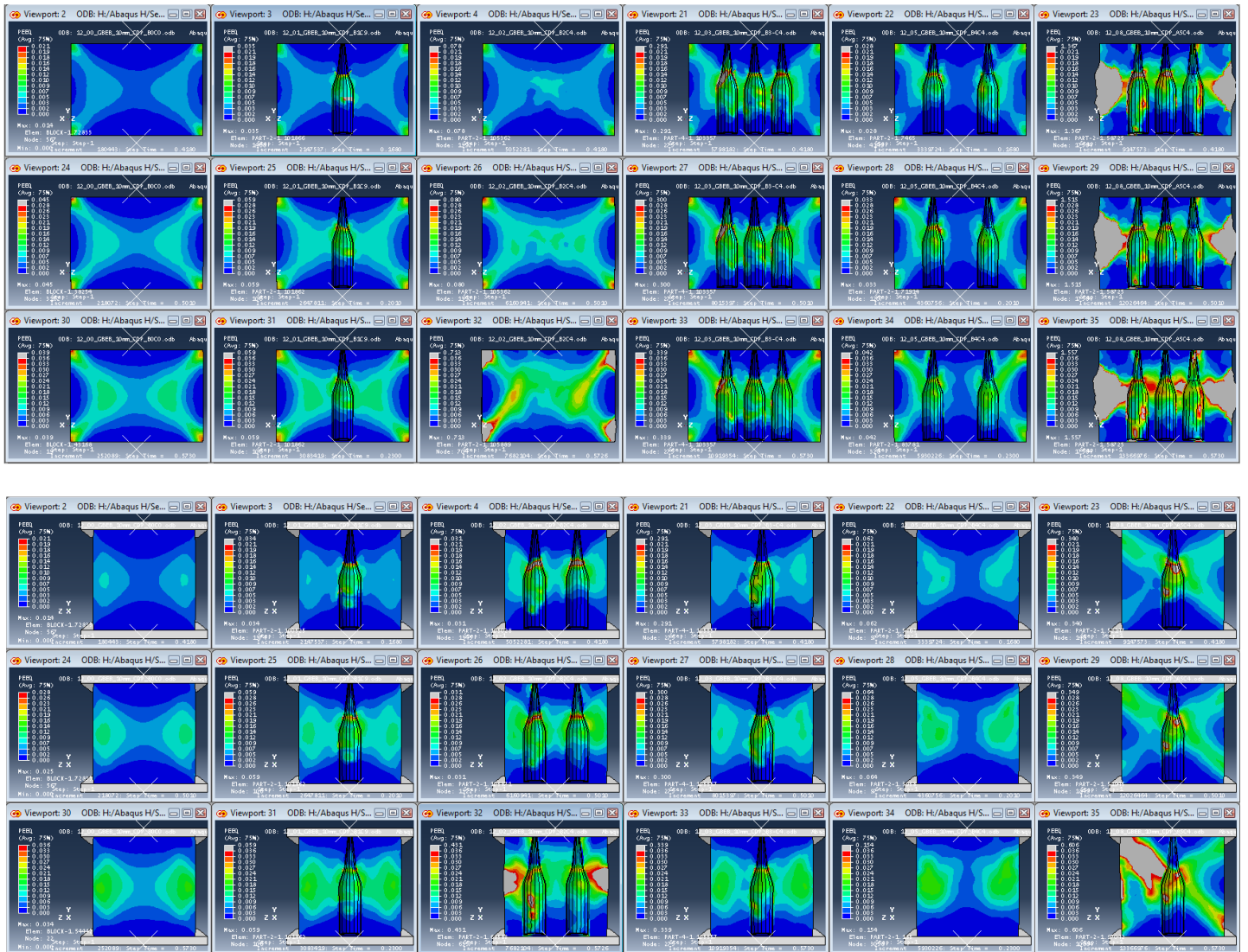


Figure 8.19: PEEQ of CGBEB type B1, B2, B3, B4 and B5 respectively (vertical cross-section diagonally and through the middle of the bottle)

8.6. Effect of merged versus unmerged geometry

A final study examined whether merging the glass and earthcrete geometries at the interface affects the response. The simulations 13_01 and 13_02 in this section use the updated material properties of earthcrete, with the compressive damage of the glass raised from 50% to 99%. The glass and the matrix share a common interface, which can either be merged or left unmerged. When the geometries are left unmerged, each part has its own nodes. Along the interface these nodes coincide in space but remain independent, so their degrees of freedom are not shared and must be coupled through a constraint. When the geometries are merged, the interfaces are merged into a single mesh: the glass and earthcrete elements connect to the same nodes and share their degrees of freedom directly.

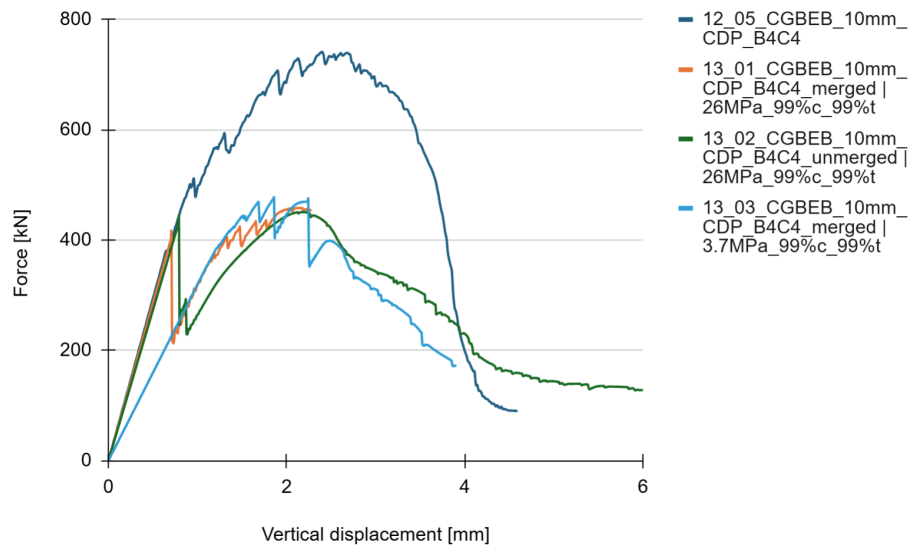


Figure 8.20: Load–displacement response for the merged and unmerged interface.

As shown in Figure 8.20, the two approaches give almost identical results, but the unmerged model required substantially more computation time. This is because the merged mesh shares nodes across the interface and therefore has fewer degrees of freedom, while the unmerged model must also resolve for the interface coupling. Since the two produce approximately the same response, the merged geometry is adopted for the remaining simulations as the more efficient choice. It must be noted that both variants represent a fully bonded interface with the same interface properties. The comparison only isolates the effect of discretization, not the bond.

A third simulation was also performed using the updated earthcrete properties and a reduced glass tensile strength, lowered from 26 MPa to 3.7 MPa—along with a stiffness reduction to 6000 N/mm. This adjustment eliminated the dip observed in earlier simulations, while the post-peak behavior remained consistent with the other cases.

8.7. Discussion of the numerical results

From the numerical simulations, it is evident that block type B4C4 exhibits a higher load-bearing capacity compared to other variants in both the B4 and B0-B5 series. Although block type B9C2 achieves the highest peak load, its post-peak response is considerably more brittle. While a more brittle post-peak behavior is expected for densely packed configurations, the corresponding increase in peak load raises questions about the reliability of this result. For these reasons, B4C4 and B5C4 were selected for further experimental testing, with the plain B0C0 block serving as a control group.

Earthcrete cover Regarding cover thickness, B4C2 (2 cm cover) exhibited lower capacity and a pronounced dip in the force-displacement curve, with tensile damage localized at the corners where the cover is thinnest. B4C4 and B4C6 performed similarly, indicating that increasing cover beyond approximately 4 cm offers no additional benefit. In B4C6, once the glass fractures, the internal core is more compromised as a load-transferring element, leaving only a 6 cm thick outer band of earthcrete to resist compression. Conversely, B4C4 retains an intact internal core that continues to contribute to load bearing. This could be one of the reasons why B4C4 is stronger than B4C6.

Bottle count For bottle count, B4C4 outperformed B1, B2, B3, and B5, suggesting that capacity increases with bottle count up to an optimal threshold (around four bottles) and decreases thereafter. However, then capacity rises for B9C2 which achieved the highest peak load (806.92 kN) but suffered the most brittle post-peak response. The stiffness also increases with bottle count due to the higher stiffness of the glass.

Merged vs. unmerged The merged and unmerged interface geometries produce nearly identical results, with the merged simulation being more computationally efficient. This suggests that merged vs. unmerged geometries only have a limited influence on the response in the numerical model. It must be noted that both variants still represent a fully bonded interface. The properties at interface level are identical. The merged vs. unmerged comparison isolates the effect of the discretization, not the bond itself. The influence of interface strength is addressed briefly through a cohesive simulation in Appendix H, which is based on the values given in section 7.7.

Limitations Several limitations should be acknowledged. The glass model does not fully capture the complexities of actual bottles, including curvature, thickness variations and surface coatings. The model also neglects long-term degradation mechanisms such as stress corrosion.

EXPERIMENTAL INVESTIGATIONS

Compression testing of different configurations

This chapter investigates force-displacement response and fracture pattern of the Cubic GBEB Type B0C0, B4C4 and B5C4 subjected to experimental compressive testing. The experimental results are then compared with the simulated numerical results to carry out a final calibration of the computational model.

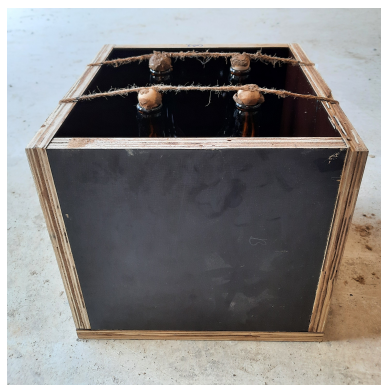
9.1. Specimen fabrication and curing

To produce the bricks, the molds are first assembled using five multiplex plates and several screws each. A thin layer of oil is applied to the interior surfaces to prevent the earthcrete from adhering to the mold plates and to facilitate easy removal.

Following this, the bottles are positioned into the mold according to their designated positions, varying according to block type. The earthcrete mortar is then prepared and poured around the bottles. To prevent the bottle from floating and to keep them in place, a string fitted with wooden beads is used. This assembly is secured to the mold with adhesive tape and manually pre-tensioned before the bottles are positioned. Each bottle is then placed directly underneath a wooden bead. Since the contact surface of the bead sits slightly lower than the opening of the bottle, the string applies a downward force, similar to the tension principle seen in cable-stayed bridges. This effectively holds the bottle in place. The bottles are arranged in the molds as depicted below.



(a) 3D view of the empty mold, configuration type B0C0



(b) Mold containing 4 bottles, configuration type B4C4



(c) Top view of the mold containing 5 bottles, configuration type B5C4

Figure 9.1: Set-up of the molds

The earthcrete mixture comprised the materials listed in Table 9.1, in the indicated proportions. The natural soil and cement were first dry-mixed thoroughly with a 40L concrete-mixer, after which water was added. Finally, the superplasticiser was incorporated to improve flow and workability. Once the mixture reached the right consistency, the mixture was poured into the molds.

Table 9.1: Material composition of 1 litre of CSRE mixture.

Material	kg	%
Natural soil	1.620	74
Cement I 52.2 R	0.194	9
Water	0.349	16
Superplasticiser PCE Mastergelenium 51	0.194	1

About halfway through the pouring of the earthcrete, the molds were shaken to compact the mixture and to release trapped air bubbles. This motion disturbed the alignment of the bottles, making them tilt and shift. Hence, the bottles needed to be readjusted to ensure they remained vertically aligned beneath the beads.

After the bottles were embedded in the earthcrete for a short period, the string was removed and an additional plate was placed over the mold. This plate was secured with adhesive tape to prevent any upward movement of the bottles during the initial curing phase. The plate also levels some of the unevenness seen on the earthcrete's surface.



(a) B4C4 at the half-pour stage.



(b) B5C4 at the fully poured stage.



(c) Top plate secured with adhesive tape

Figure 9.2: Steps in the pouring process

The uncured bricks were then left to rest in an ambient temperature room, at the Stevinlab. At the 7-day mark, the molds were dismantled. The bricks were allowed to cure for a total of 28 days to ensure the material achieved its design strength.

On day 27, an additional layer of CFSG1 (Cuglaton Fast Setting Grout) was applied to the top of block types B4C4 and B5C4 to smooth any surface irregularities. The 10 mm grout layer also serves as a protective barrier, preventing direct contact between the glass and the compression bench's top plate. The same treatment was not required on the underside of the blocks given that in all cases, the bottoms of the bottles were found to sit slightly above the block bottoms.

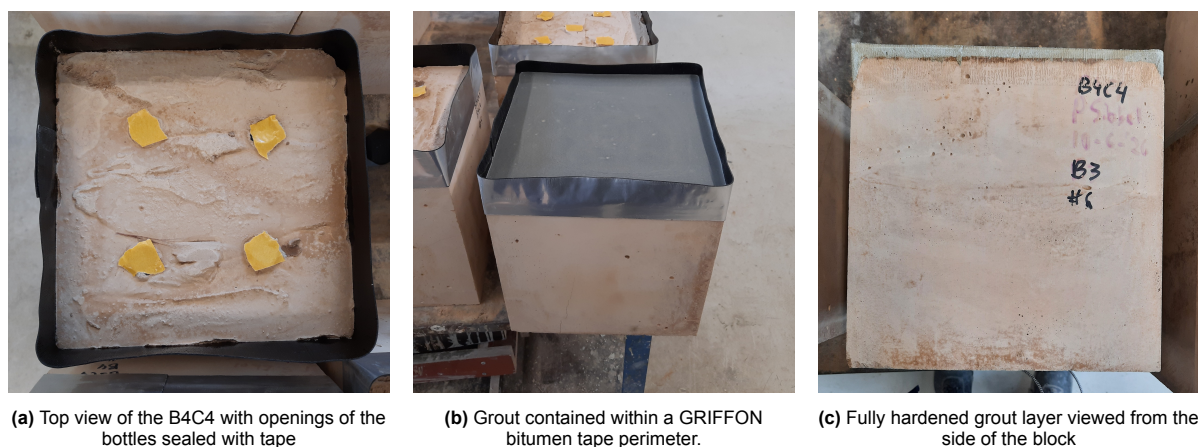


Figure 9.3: Steps during grout application

9.2. Visual inspection of specimens

Despite the compaction efforts, certain surfaces exhibited imperfections in the form of air voids or localized edge chipping. These surface defects are documented in the images presented in Figure 9.4. Furthermore, the bottles were found to sit slightly above the bottom surface of the blocks and therefore were not visible. This is most likely due to insufficient pressing down of the bottles after compaction. In one single case, the concave bottom portion of a bottle was visible. However, the knurled surfaces still did not align flush with the bottom surfaces of the block, meaning that the glass was not in contact with the steel during the testing.

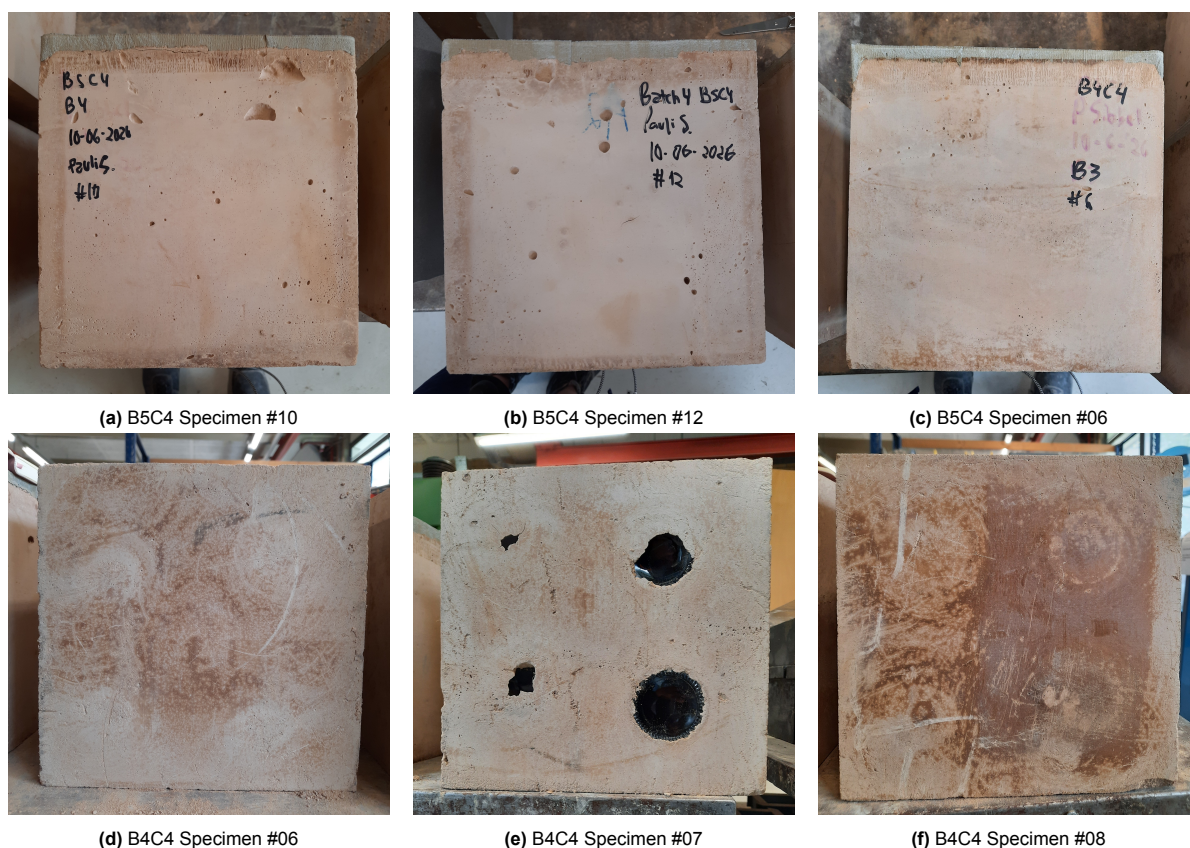


Figure 9.4: Visual inspection of the specimens (upper row with imperfections & bottom row showing the bottom of the blocks)

On the bottom surfaces of the blocks, faint outlines of the bottles were also visible, most likely caused

by localized densification of the earthcrete beneath the bottles during compaction, combined with downward pressure applied to the bottles.

9.3. Results from compressive testing of the CGBEB

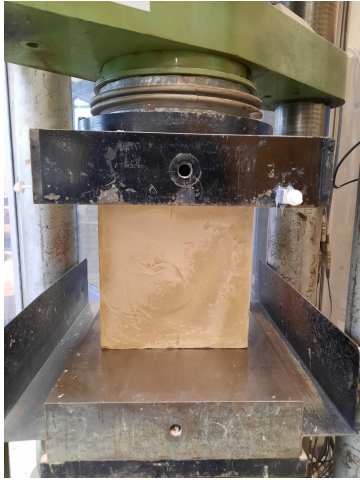


Figure 9.5: Compressive testing setup for CGBEB specimens

The experimental tests were performed on the blocks to identify differences and similarities in crack patterns and damage regions compared to those observed from the numerical simulations conducted in Abaqus. This allows for an assessment of the numerical model's validity and deepens our understanding of the interaction between the two materials.

Following the curing period, each specimen was subjected to compressive loading at a rate of 0.01 mm/s. The test was terminated upon complete structural failure of the specimen. A displacement value of 10 mm was set for B0C0 specimens, while B4C4 and B5C4 specimens were tested up to a value of 8 mm.

The B0C0 blocks were rotated onto their smoother side to compensate for the rough top surface left by the earthcrete pouring. This measure was not required for the B4C4 and B5C4 specimens, due to the previously mentioned grouting layer.

9.3.1. Load-displacement curves

The blocks type B0C0, B4C4 and B5C4 behave in a near-identical manner within each series, indicating reliable and repeatable experimental execution. Averaged curves were computed for each configuration to allow direct comparison between them.

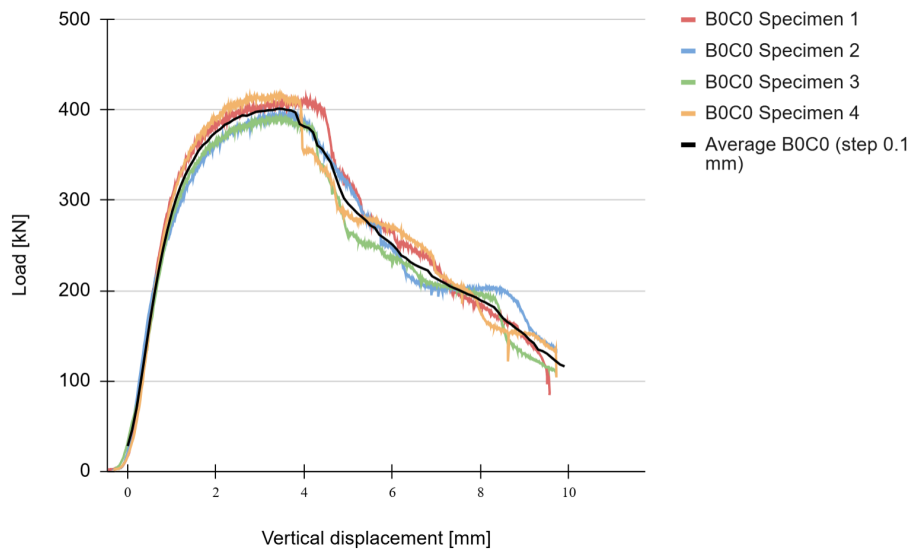


Figure 9.6: Load-displacement curves of the experimental data for specimens B0C0 with the averaged curve manually reduced to 0.1 mm displacement increments.

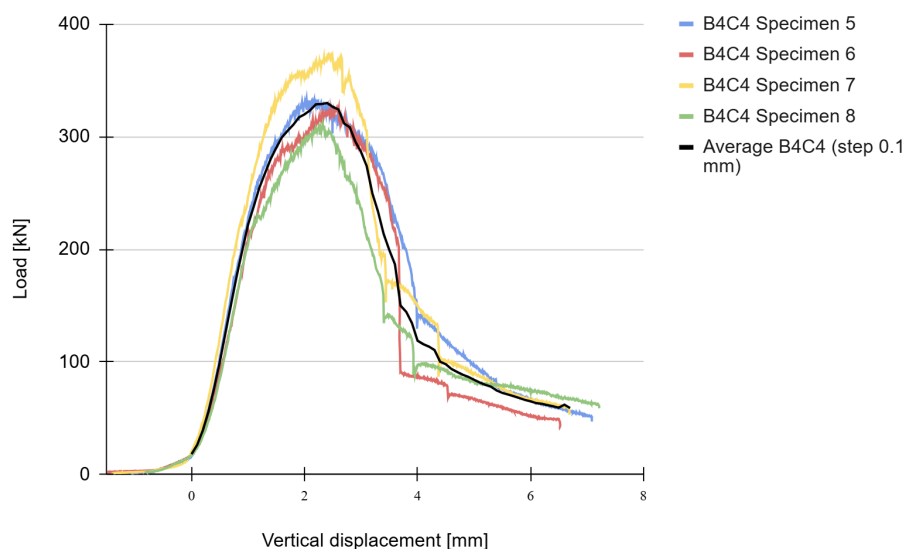


Figure 9.7: Averaged and load–displacement curves for specimen B4C4, with the averaged curve manually reduced to 0.1 mm displacement increments.

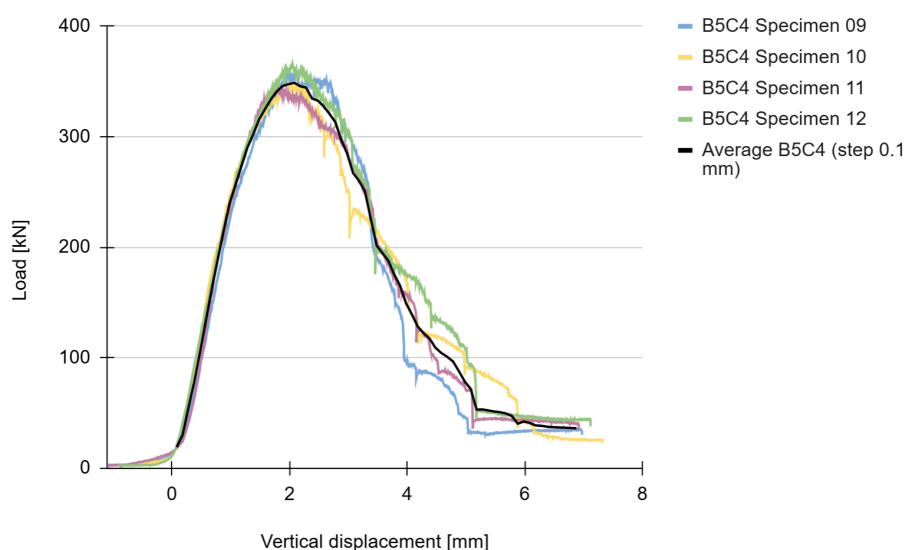


Figure 9.8: Averaged and load–displacement curves for specimen B5C4, with the averaged curve manually reduced to 0.1 mm displacement increments.

The averaged load–displacement curves depicted in Figure 9.9 show that all three configurations follow a similar initial linear elastic path, with a linear rise to about 220 kN. The linear elastic phase is followed by a uniform plastic deformation region, which extends until the peak load is reached. In this phase, cracking initiates in both the glass and the earthcrete matrix, which is reflected in the oscillating (up-and-down) response of the previous curves.

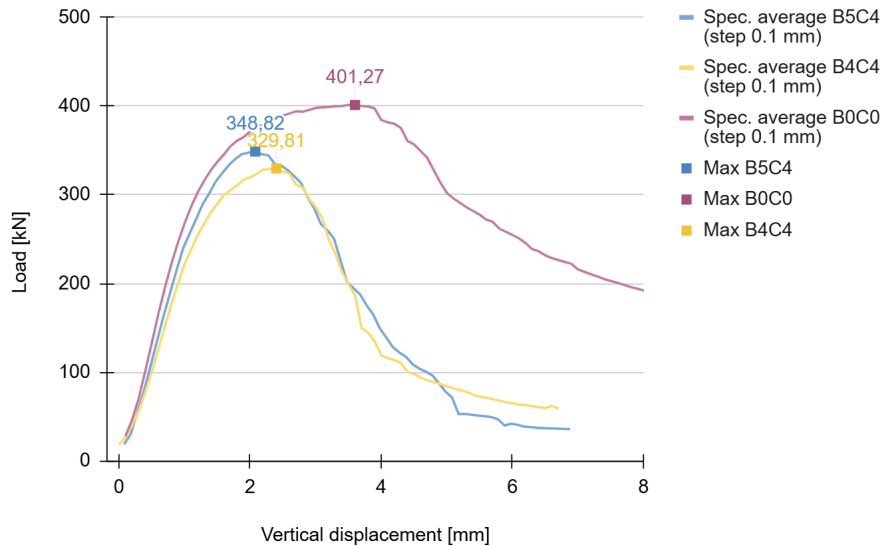


Figure 9.9: Averaged load–displacement curves for configurations B0, B4, B5

After the peak load is reached, the glass-containing specimens (B4 and B5) exhibit a more rapid loss of load capacity compared to B0. The latter configuration exhibits a more ductile response and reaches a higher peak load of 401 kN. Between the two glass-containing configurations, B5 outperforms B4. This is surprising as B5 contains more glass and less earthcrete. The central bottle seems to thus make a slight positive difference in load carrying capacity. Given the small sample size, however, this observed advantage could stem from experimental variability rather than true mechanical improvement.

The initial stiffness is nearly identical across all three configurations, though B0C0 exhibits a slightly higher value than B4C4 and B5C4. This is likely because the embedded glass bottles contain “empty” space, which reduces the overall composite stiffness compared to the solid, fully compacted earthcrete matrix of B0C0.

9.3.2. Experimental fracture pattern

Configuration B0C0

Cracks of configuration B0 started near the vertical edges of the cube, running generally parallel to the applied load. As the load approached the ultimate strength, these cracks coalesced, developing into splitting cracks. The top and bottom loading plates subjected the cube to frictional restraints which prevented localized lateral expansion while the mid-height region remained free to deform. This difference in restraint follows the so-called “barrel” effect, where the central portion of the cube expands outwards while the loading surfaces remain constrained.

As displacement increased, entire segments of the sides were splintered from the block. At approximately 10 mm of displacement, the remaining specimen assumed an hourglass or truncated pyramidal shape. The central core remained largely intact.

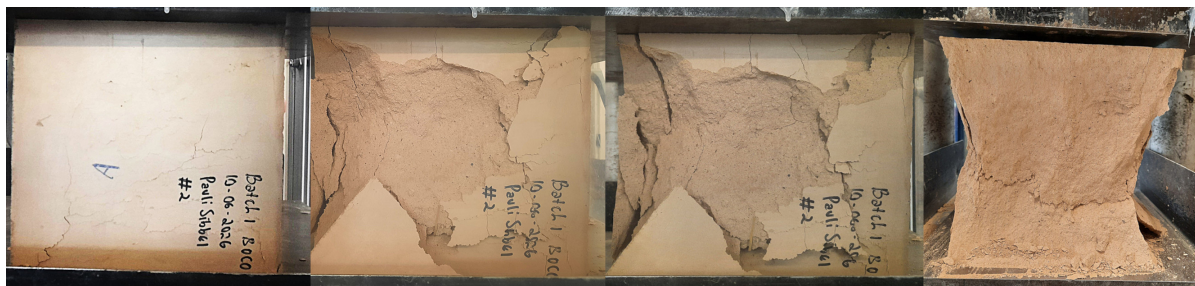


Figure 9.10: Typical cracking progression for B0C0

Configuration B4C4 and B5C4

In contrast to B0C0, the B4C4 and B5C4 configurations exhibited a greater number of vertical fracture lines, mainly localized near the cube edges. Despite there being air voids present on the surface (as seen in Specimen #10 in Figure 9.12), these did not appear to influence the crack paths. After the removal of wedge shaped fragments, the remaining specimen also assumed a truncated pyramidal geometry due to the previously mentioned “barrel” effect. The remaining material was significantly more brittle and crumbled easily due to the complete fracture of the glass content, compromising its structural integrity.

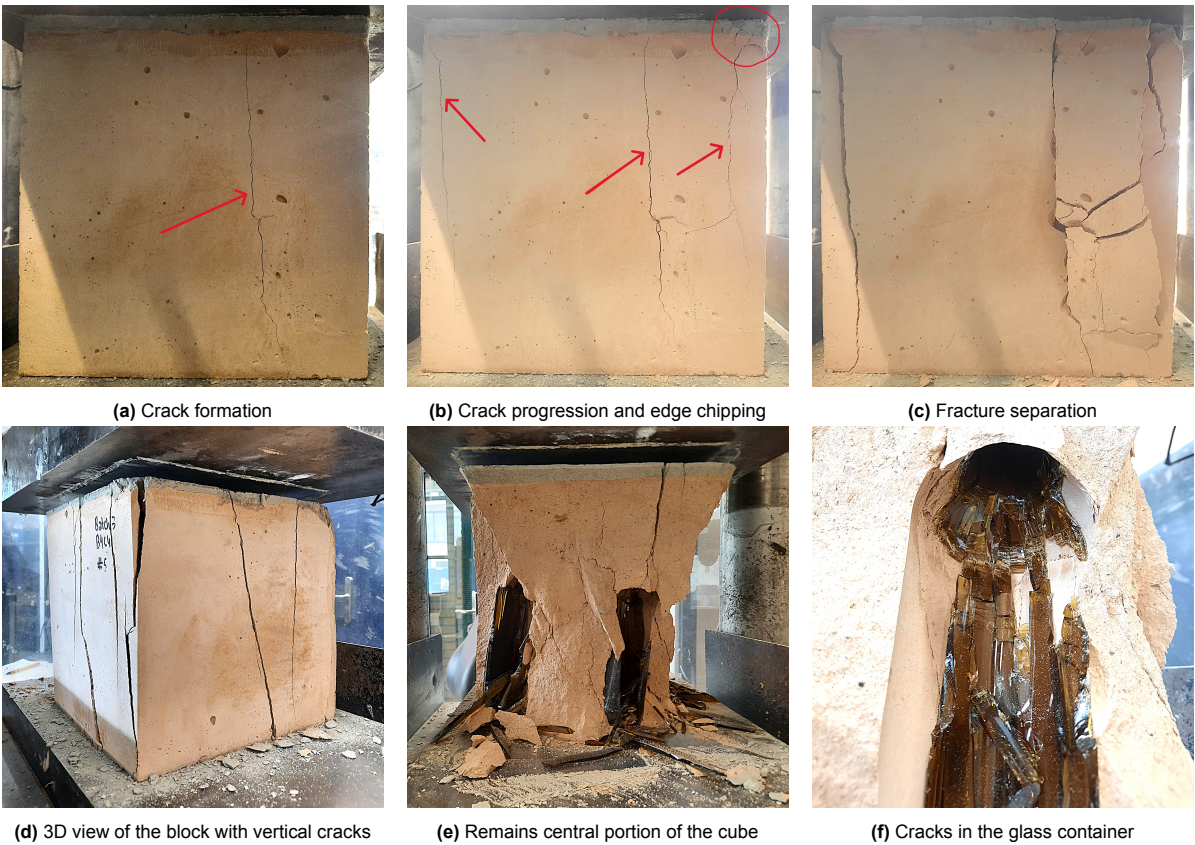


Figure 9.11: Fracture progress of B4C4 nr. #5

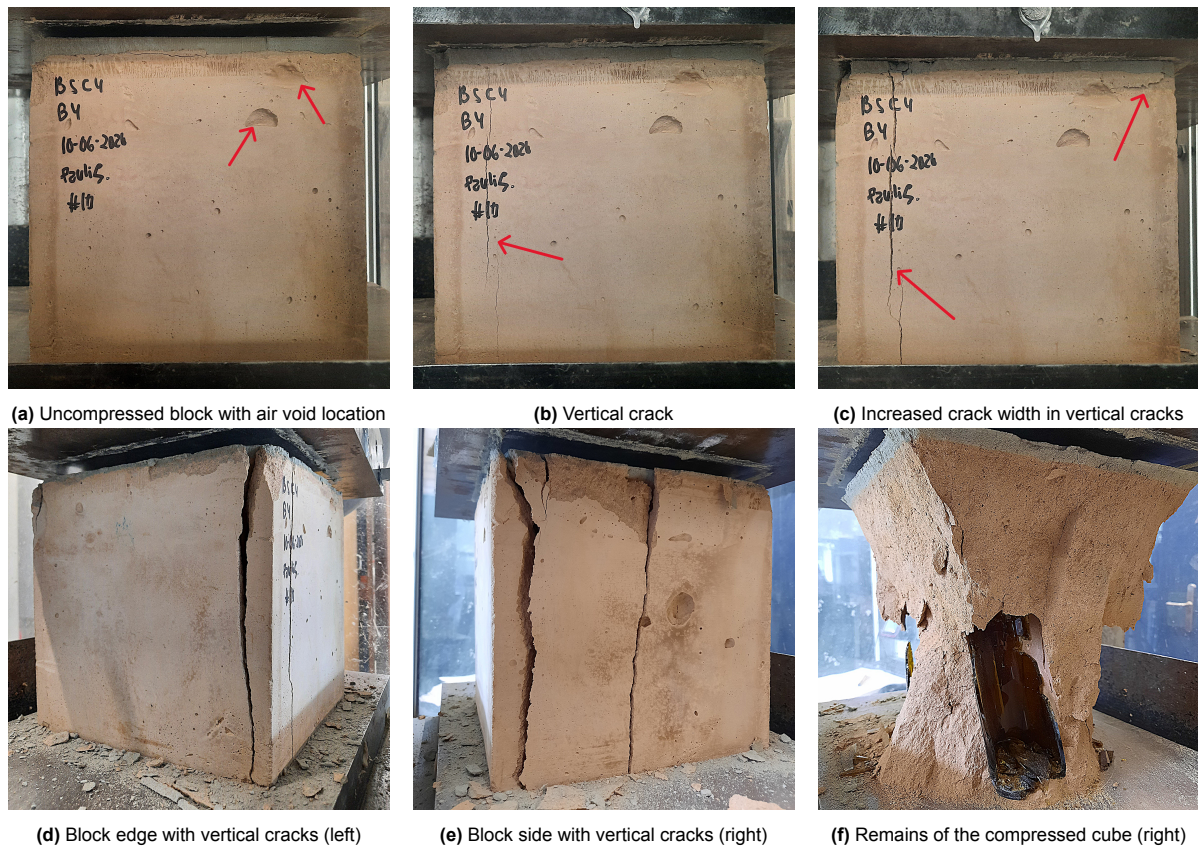


Figure 9.12: Fracture location and progress of B5C4 nr. #10

Some of the bottles were not perfectly vertical as depicted in the figures above and also in appendix G. However, since the force–displacement curves were largely consistent across specimens in each type, it can be assumed that this misalignment does not significantly influence the results (see appendix G.2 for rough estimates of the incline angles). Moreover, pulverization of the bottle heels and shoulders under compressive stress was observed experimentally and assumed also in the numerical simulations by the tensile damage regions.

9.3.3. Comparison of experimental and numerical load-displacement Curves

The simulated results for earthcrete specimen 12_00_CGBEB_10mm_CDP_B0C0 deviate significantly from the experimental data, as depicted in Figure 9.13. The numerical model predicts a more brittle response than observed experimentally, and the peak force is approximately 40% higher than expected. This discrepancy likely stems from multiple factors, including an overestimation of the earthcrete strength in the material model, as well as the fact that the input parameters were originally calibrated using smaller prismatic specimens, which do not perfectly translate to the cubic geometry.

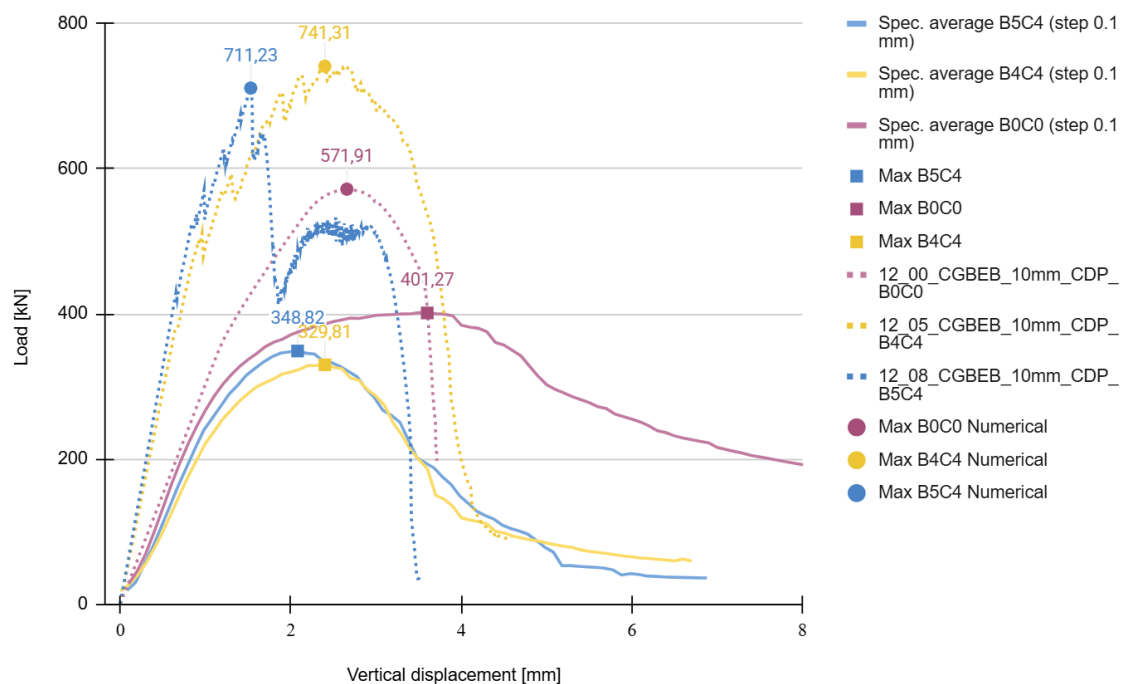


Figure 9.13: Comparison of Experimental and Numerical Load-Displacement Curves

The numerical model predicts an increase in stiffness and load capacity with bottle addition, yet the experiments show the opposite. This indicates that the compressive damage parameter of the glass should be increased to limit its load-transfer contribution and the stiffness and tensile strength of the glass should be lowered.

Table 9.2: Comparison of experimental and numerical peak loads

Specimen	Experimental Peak (kN)	Numerical Peak (kN)	Num./Exp. (%)	Discrepancy (%)
0C0	401.27	571.91	142.53	42.53
B4C4	329.81	741.31	224.77	124.77
B5C4	348.82	711.23	203.90	103.90

$$* \text{ Difference} = |\text{Num} - \text{Exp}| / \text{Exp} \times 100\%$$

The numerical model consistently overestimates the load-bearing capacity of the cubes, with discrepancy percentages ranging from 42.5% for B0C0 to 124.8% for B4C4. Further calibration of the material properties is therefore necessary to improve the predictive accuracy of the numerical model. The experimental results for B0C0 can serve as an initial reference for adjusting these properties.

9.3.4. Comparison experimental and numerical damaged area

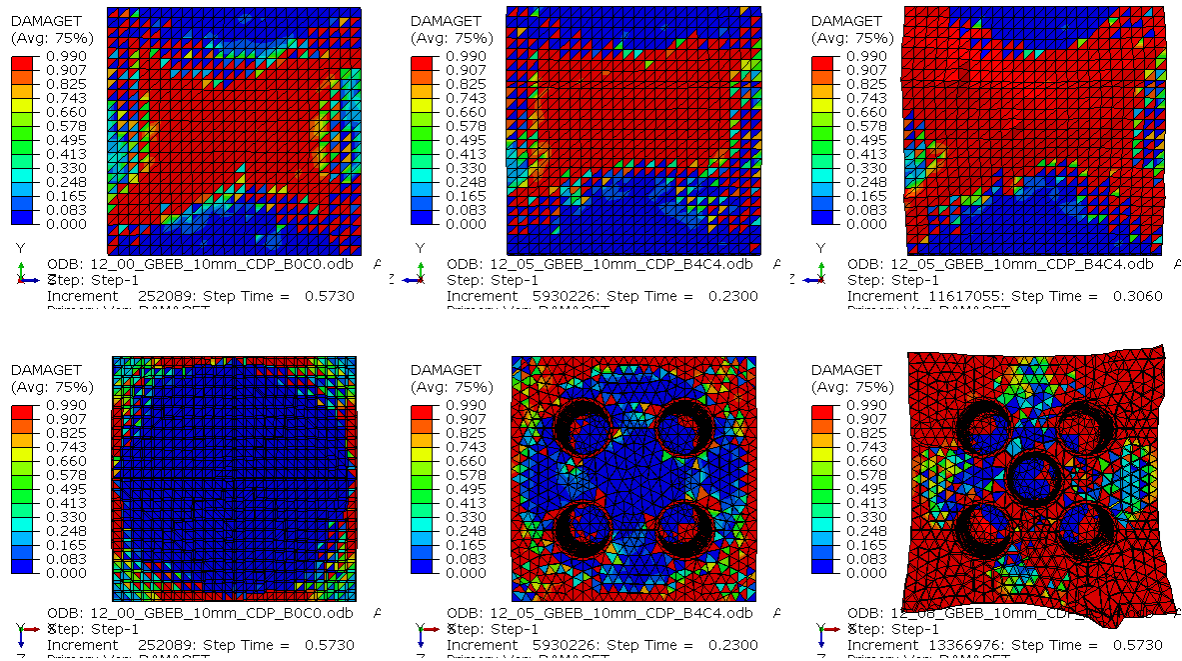


Figure 9.14: Damaged region: numerical results

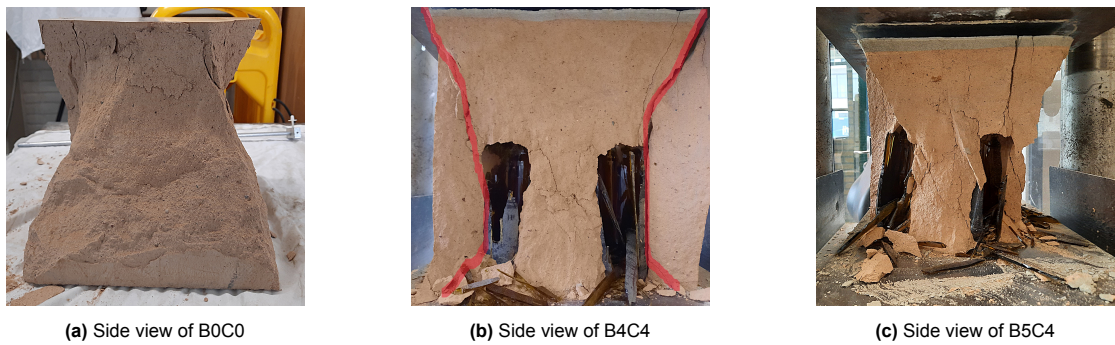


Figure 9.15: Damaged region: experimental results

A clear overlap is observed among the results presented above. The B5C4 configuration, in particular, showed more pronounced corner crushing, which yielded a more slender central core. Wedge-shaped fragments detached from all blocks, a failure mode also captured in the numerical models. However, the damaged zone in the B0C0 numerical model remained confined within the lateral surfaces of the cube. As previously illustrated, the material properties used in the numerical simulations do not fit the experimental results well. It would therefore be of interest to do one last iteration to investigate which changes need to be made to obtain more reasonable results.

III. Final numerical calibration

The comparison in Chapter 9 showed that the numerical models over-predict the experimental peak loads by a large margin. This chapter closes the numerical–experimental–numerical loop by recalibrating the material models against the CGBEB experimental results. The earthcrete model is recalibrated first against the plain block (B0C0). The resulting parameters are then transferred and readjusted in the B4C4 block. The final iteration of the material model is then tested on the B5C4 block.

10.1. Numerical calibration of B0C0

Because the simulated results for earthcrete specimen 12_00_CGBEB_10mm_CDP_B0C0 deviated significantly from the experimental data, the material properties needed to be re-calibrated with a 10 mm mesh. From the conversion of the force–displacement ($F-u$) data to stress–strain ($\sigma-\varepsilon$) curves, and subsequently to inelastic strain and stress using the formulas given in Chapter 5, a baseline model was created for earthcrete. This configuration corresponds to Model 14_00_CGBEB_10mm_B0C0.

After this, a reduction factor was applied to the stress values to lower the overall stress level, resulting in material model 14_02_CGBEB_10mm_B0C0. Finally, the strain values were increased to allow for a more ductile response. This final adjustment yielded a calibrated numerical model, designated Model 14_03_CGBEB_10mm_B0C0 which represents a better fit.

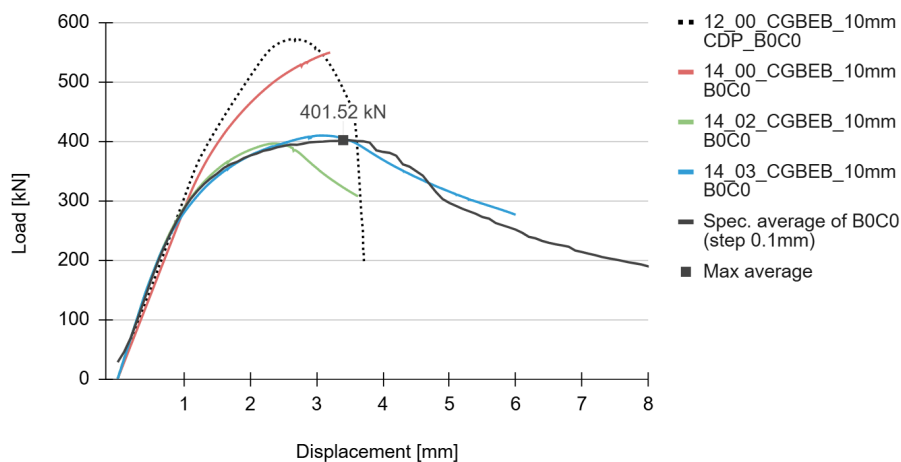


Figure 10.1: Calibration of the material properties post experimental testing of B0C0

10.2. Numerical calibration of B4C4

Following this, block type B4C4 was re-simulated using the recalibrated material properties from Model 14_03_CGBEB_10mm_B0C0. The first iteration, however, yielded a load-bearing capacity which far exceeding the required level (G_1), as depicted in figure 10.2. This indicates that the tensile yield stress of glass was modeled as too high, enabling it to continue transferring a disproportionate share of the applied load. To address this, the glass material properties were reduced to the values provided by Hoessein Alkisaee (G_2), listed below. As shown in Table 10.1, the tensile yield stress is substantially lower, also accounting for the effects of stress corrosion.

Glass material model	Tensile Behaviour		Tension Damage	
	σ_t (MPa)	ε_{cr}	d_t	ε_{pl}
G_1	26.000	0.000	0.000	0.000
	0.260	5.90×10^{-4}	0.990	5.90×10^{-4}
G_2	3.714	0.000	0.000	0.000
	0.037	6.19×10^{-4}	0.990	6.19×10^{-5}
	Compressive Behaviour		Compression Damage	
	σ_c (MPa)	ε_{in}	d_c	ε_{pl}
G_1	800.0	0.000	0.000	0.000
	400.0	8.80×10^{-4}	0.500	1.00×10^{-5}
G_2	800.0	0.000	0.000	0.000
	8.0	1.33×10^{-1}	0.990	1.33×10^{-3}

Table 10.1: Glass tensile and compressive behavior with damage parameters for v_1 and v_2

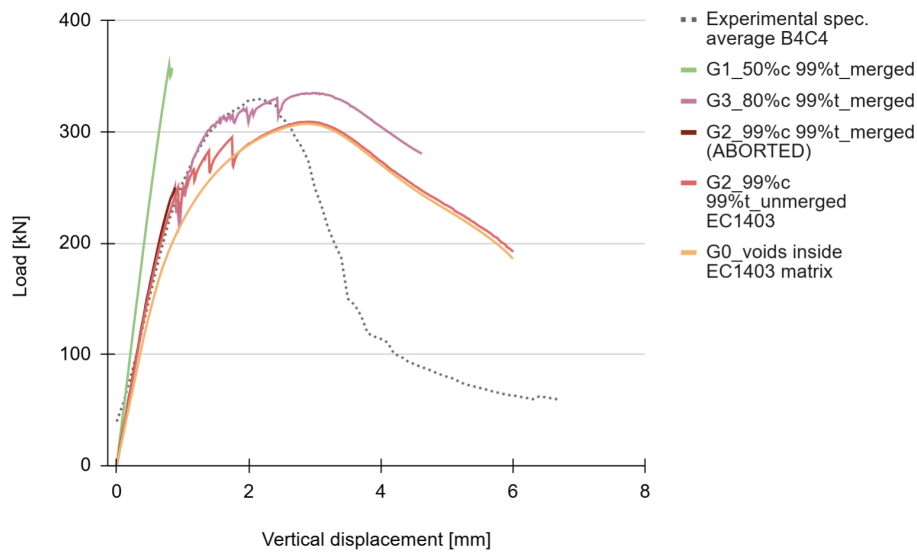


Figure 10.2: Calibration of the material properties of B4C4 post experimental testing

However, the simulation with material properties G_2 was aborted due to a numerical instability, in which the ratio of the deformation speed to the wave speed exceeded 1.0 in at least one element. To mitigate this, the compressive damage parameter of the glass was lowered from 99% to 80% (G_3). As shown in the figure above, the inelastic region of model G_3 is still not sufficiently brittle. Subsequently, the glass volume was removed from the earthcrete entirely, in order to isolate its effect on the overall response of the cube. Removing the glass lowers the capacity and renders the post-peak response

slightly more brittle. Nevertheless, the descending branch does not reach the desired steepness, which can be attributed to the stress–strain values assigned in the material model of the earthcrete.

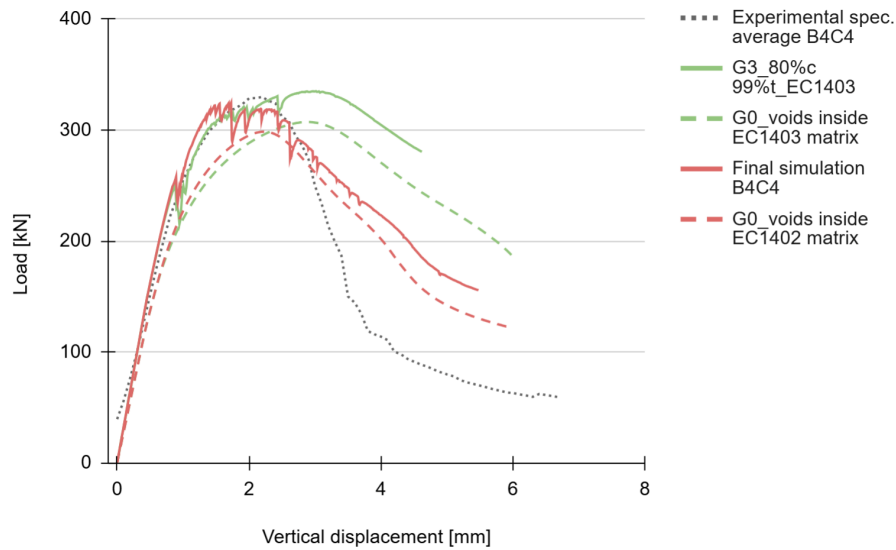


Figure 10.3: Final calibration of the material properties of B4C4 post experimental testing

The final B4C4 iteration consisted of further limiting the load-bearing contribution of the glass by increasing its compressive damage parameter from 80% to 90%. The model with voids (i.e., without glass) exhibited a considerably smoother response than the glass-containing model. The glass in this case is considered to be slightly reinforcing. The first dip (at $u=0.89$ mm) in the force-displacement curve corresponds to the onset of glass fracture at the shoulder and heel regions. Subsequent dips reflect progressive stages of glass fragmentation and earthcrete deformation. The final image in Figure 10.4 at 4 mm of displacement shows that tensile damage within the earthcrete remains largely confined to the lateral faces, even after glass fracture has occurred.

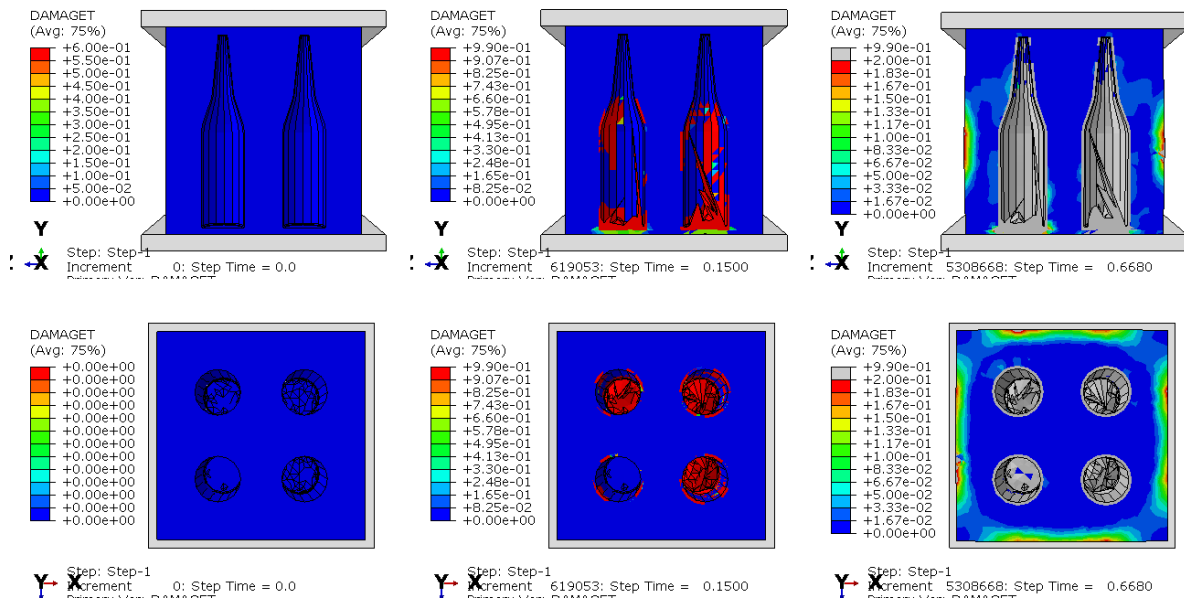


Figure 10.4: Simulation G4_90%c 99%t_EC1402 at $u=0$ mm, $u=0.89$ mm (at first big dip) and $u=4$ mm

When the aforementioned material properties are applied to the B5C4 model, the load-bearing capacity

does not increase. Instead, it remains comparable to that of B4C4. Moreover, the post-peak behavior becomes more brittle, while the stiffness remains unchanged relative to the B4C4 configuration. Consequently, the numerical response fails to reflect the experimental results.

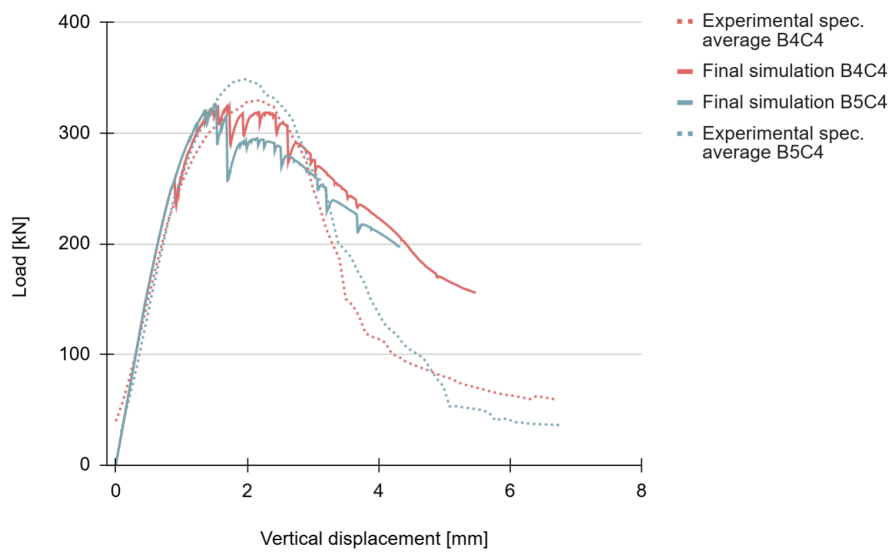


Figure 10.5: Final simulation of B4C4 (model G4_90%c 99%t_EC1402) and B5C4

An additional simulation was performed on a variant of the B4C4 block in which two of the four bottles are inverted by 180 degrees. The alternating orientation spreads the shoulder-initiated fracture zone over the midsection of the block, resulting in a slightly more ductile post-peak response. The overall difference between the two configurations remains small, however, so the bottle orientation is of minor influence on the global response. The full results are presented in Annex I.

10.3. Numerical calibration of B4C4 with GFI (Fracture energy)

As discussed in Section 6.4, an alternative approach for predicting the tensile behavior involves specifying a fracture energy value, G_f , instead of stress–strain values. In the aforementioned section, a fracture energy of 0.001 N/mm was calibrated for a single glass bottle with a 10 mm mesh and applied to the cubic model. When the stiffness proved inadequate, the modulus of elasticity was reduced from 45,500 MPa to 6,000 MPa to match the experimental data. The 26 MPa tensile strength resulted in excessive capacity. With the fracture energy included, the response showed a sharp spike followed by a sudden drop upon glass fracture, indicating an unrealistically abrupt loss of capacity. Reducing the tensile strength to 3.7 MPa gave a smoother response, but the simulation was terminated due to the high computation time and the deviation from the experimental average. Overall, G_f does not appear to be a suitable predictor for this model, as it introduces dips that are not observed experimentally.

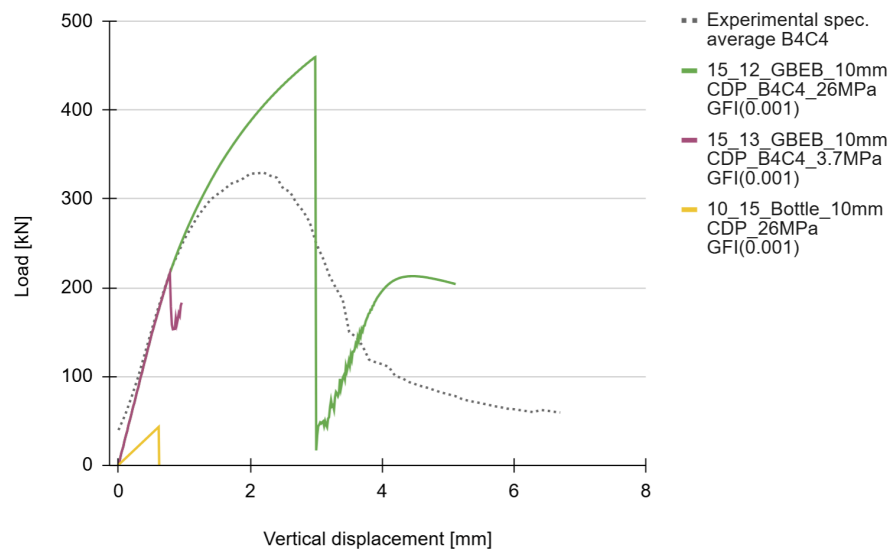


Figure 10.6: Calibration of the material properties of B4C4 post experimental testing with GFI

10.4. Discussion

10.4.1. Experimental Findings

The force-displacement curves from the experimental testing within each configuration of the Cubic Glass Bottle Earthcrete Block (CGBEB) confirm a reliable and repeatable fabrication and test protocol.

Block type B0C0 The plain block B0C0 exhibited the highest load-bearing capacity (401 kN) and the most ductile post-peak response among the 3 types. Because this type did not contain embedded bottles, a more homogeneous matrix with less air voids could be achieved. This was also noticeable in the disassembly of the molds, where fewer air voids could be detected at surface level. After testing, a clear truncated pyramidal geometry remained, with an intact central core. The plain B0C0 block also demonstrated a slightly higher stiffness.

Block type B4C4 The B4C4 blocks reached a mean load-bearing capacity of 330 kN, lower than B0C0 (401 kN), and showed a more brittle post-peak response. This is overall not a very favorable result as usually ductility in structural elements provide warning signs before failure and allow additional stress redistribution. Scatter among specimens was more pronounced for this configuration. Although the mold dimensions were consistent, variations in the grouting layer may have some contribution to this scatter. However, the lack of detailed layer-thickness measurements prevents a definitive assumption. Specimen #7, in particular, showed a noticeable higher capacity, yet no remarkable feature in its fracture pattern could justify this increase. Additionally, no extreme misalignment of the bottles or absence thereof could be observed.

Block type B5C4 B5C4 attained a slightly higher mean capacity (349 kN) than B4C4, suggesting a possible beneficial role of the central bottle. One explanation for this higher capacity may be due to a more effective load redistribution among the bottles. If one bottle were to engage the load earlier than the others, the load would become concentrated on that single bottle, potentially leading to premature fracture and an asymmetric global response. In the five-bottle configuration, however, load redistribution occurs more effectively, making this localized effect less pronounced than in the B4 configuration. Nevertheless, given the small sample size, this improvement may equally be due to experimental variability. The post-peak behavior remained brittle, mirroring that of B4C4.

Stiffness and bottle alignment The stiffness for both glass-containing block types was lower than B0C0, which is likely due to the unutilized internal voids created by the glass bottles: voids that cancel out the higher stiffness of the glass material itself. As a result, the stresses are mostly redistributed to the matrix. The glass also compromises the structural integrity post-fracture, creating weak spots where damage can spread further into the matrix. Furthermore, slight deviations from vertical orientation due to the shaking of the molds might affect load transfer mechanisms. Although it is uncertain whether bottle misalignment has a positive or negative effect on capacity, it can be deduced that if alignment is off, then one side of the bottle experiences greater stress concentration at the heel and opening, leading to early failure.

Fracture pattern Fracture patterns across configurations B4 and B5 showed similarities. All blocks exhibited vertical splitting cracks initiating near the cube edges, with wedge-shaped fragments detaching progressively. The glass-containing specimens displayed a greater density of vertical fracture lines at locations where the earthcrete cover was the thinnest. This reflects areas of high stress concentration (weak points). The pulverization of bottle heels and shoulders also confirms that these regions act as critical stress concentration zones.

10.4.2. Numerical Findings

Numerical simulations (I) vs. Experimental results The comparison with the numerical model is the key finding: the model overestimates stiffness and capacity (by 42.5% for B0C0 up to 124.8% for B4C4). Numerically, capacity increases with bottle count (with B0C0 exhibiting the lowest values), whereas experimentally, B0C0 exhibits the highest capacity. The stiffness going from B4 to B5 increases both experimentally and numerically. But B0C0 shows higher relatively the stiffness experimentally, whereas numerically it has the lowest stiffness. This trend reversal suggests that the numerical model fails to capture the actual mechanical contribution of the embedded glass bottles. Several factors likely contribute to the observed discrepancies:

Geometric Simplifications The numerical model accounts for perfectly vertical, flaw-free bottles overlooks the subtle misalignment and surface imperfections present in experimental specimens.

Size Effects The transition from prismatic specimens (used for calibration) $150 \times 150 \times 240$ mm to cubic specimens $240 \times 240 \times 240$ mm introduces size effects that could explain stiffness and compressive and tensile strength variation in the material properties.

Calibration Outcomes The recalibration process, particularly Model 14_03 for B0C0, successfully reproduced the plain block response by applying reduction factors to stress values and increasing strain values to achieve a more ductile response. However, these material properties could not be validated when implementing them in the B4C4 blocks. On the other hand, earthcrete model 14_02 gave a better result and is more predictive for blocks type B4C4 and B5C4. Glass properties were also substituted with G_2 values (3.714 MPa tensile strength versus 26 MPa in the original model) and later G_4 values. When glass with 26MPa strength is surrounded by the earthcrete matrix, its influence is overestimated significantly.

Fracture energy The fracture energy (G_f) approach proved unsuitable, introducing unrealistic sudden capacity drops not observed experimentally.

11

Wall design

This chapter applies the experimental results of Chapter 9 to the design of a load-bearing wall in a two-storey residential building. Because design codes for glass-bottle-embedded earthcrete masonry do not exist, the verification will follow the limit state framework for unreinforced masonry of Eurocode 6 (EN 1996-1-1), with load combinations according to EN 1990. The design strength is calculated directly from the B4C4 experimental compression tests.

11.1. Design approach

At the ultimate limit state (ULS), a vertically loaded unreinforced masonry wall must satisfy

$$N_{Ed} \leq N_{Rd} = \Phi t f_d \quad (11.1)$$

where N_{Ed} is the design vertical load per unit length of wall, Φ the capacity reduction factor for slenderness and load eccentricity, t the wall thickness and f_d the design compressive strength of the masonry. The design load can be calculated by taking two ULS combinations of EN 1990 for consequence class CC2 into consideration:

$$N_{Ed} = \max (1.35 G_k + 1.5 \psi_0 Q_k ; 1.2 G_k + 1.5 Q_k) \quad (11.2)$$

with $\psi_0 = 0.4$ for residential floor loads (Category A) and $\psi_0 = 0$ for roof loads (Category H).

11.2. Design strength from the B4C4 experiments

The three B4C4 specimens failed at a near-identical average load of 329.81 kN with a loading area of $240 \times 240 \text{ mm}^2$ which corresponds to a mean unit compressive strength of

$$f_{mean} = \frac{329.81 \cdot 10^3}{240 \cdot 240} = 5.73 \text{ MPa}. \quad (11.3)$$

The characteristic compressive strength is taken as $f_k = f_{mean}/1.2 = 4.77 \text{ MPa}$ (EN 1052-1). Given the very low scatter between specimens (Section 9.3), the mean-based value governs. It is assumed that the blocks will not be individually produced, but rather the wall will be built as a whole.

Because the units are not produced under certified factory control and the material system is new, the most conservative Eurocode 6 material factor is adopted, $\gamma_M = 2.2$ (Category II units, execution control class 2), giving

$$f_d = \frac{f_k}{\gamma_M} = \frac{4.77}{2.2} = 2.17 \text{ MPa}. \quad (11.4)$$

11.3. Case study: two-storey residential building

11.3.1. Geometry and assumptions

A two-storey residential building is considered of $8.0 \times 4.0 \text{ m}$ in plan per residence, with load-bearing walls and two facade walls. The reinforced concrete floor and roof slabs (150 mm) span one-way

over 4.0 m from wall to wall. A representative (central) wall therefore carries the loads over a width of 4.0 m. The clear storey height is 2.6 m and the wall consists of earthcrete with embedded bottles in configuration B4C4, with $t = 240$ mm and finished with 12 mm of plaster on both faces.

The following assumptions are made:

- The bulk unit weight of the B4C4 wall is $\gamma_{wall} = 16.32$ kN/m³, based on the measured earthcrete density of 1797.8 kg/m³; this corresponds to a B4C4 block mass of approximately 23.0 kg.
- Roof: 150 mm RC slab including waterproofing and finishes, $g_{roof} = 4.0$ kN/m²; imposed roof load $q_{roof} = 1.0$ kN/m² (Category H, $\alpha \leq 15^\circ$).
- Floor: 150 mm RC slab including finishes, $g_{floor} = 4.3$ kN/m²; imposed floor load $q_{floor} = 1.75$ kN/m² (Category A, non-communal residential floors per the Dutch National Annex to EN 1991-1-1).
- Plaster: $\gamma = 20$ kN/m³, 12 mm per face.
- With a building height below 10 m and walls stiffened by RC slabs at every level, wind loading is not governing for the vertically loaded interior wall and is not considered here.

11.3.2. Loads per storey

Table 11.1 shows all loads acting on the wall in question, from the build-up to the resulting line load per meter of wall. Slab loads are converted to line loads by multiplying them with a width of 4.0 m. The wall self-weight acts directly per meter of wall.

Table 11.1: Characteristic loads on the central wall (tributary width 4.0 m, storey height 2.6 m).

Load	Build-up	Line load [kN/m]
<i>Permanent (dead) loads</i>		
Roof slab	$0.15 \times 25 = 3.75$ kN/m ² $\times 4.0$ m	15.0
Roof finishes	0.25 kN/m ² $\times 4.0$ m	1.0
Roof total	$g_{roof} = 4.0$ kN/m ²	16.0
Floor slab	$0.15 \times 25 = 3.75$ kN/m ² $\times 4.0$ m	15.0
Floor finishes	0.55 kN/m ² $\times 4.0$ m	2.2
Floor total	$g_{floor} = 4.3$ kN/m ²	17.2
B4C4 wall	$16.32 \times 0.24 \times 2.6$	10.18
Plaster (2 faces)	$2 \times 20 \times 0.012 \times 2.6$	1.25
Wall total (per storey)		11.4
<i>Variable (imposed) loads</i>		
Roof, Category H ($\psi_0 = 0$)	1.0 kN/m ² $\times 4.0$ m	4.0
Floor, Category A ($\psi_0 = 0.4$)	1.75 kN/m ² $\times 4.0$ m	7.0

11.3.3. Design resistance

A capacity reduction factor of $\Phi = 0.75$ is adopted for all sections. The design resistance of the wall then becomes

$$N_{Rd} = \Phi t f_d = 0.75 \times 240 \times 2.17 = 390 \text{ kN/m.} \quad (11.5)$$

11.3.4. Load values and verification

Table 11.2 brings together the characteristic loads of Table 10.1 for the two storeys and calculates both ULS combinations at each level, with the floor load as leading variable action ($\psi_{0,floor} = 0.4$) and the roof load as the secondary action ($\psi_{0,roof} = 0$). The critical section is the base of the ground-storey wall.

At the governing section: $G_k = 16.0 + 17.2 + 2 \times 11.4 = 56.0$ kN/m, and

$$N_{Ed,a} = 1.35 \times 56.0 + 1.5 \times 0.4 \times 7.0 = 79.8 \text{ kN/m} \quad (11.6)$$

$$N_{Ed,b} = 1.2 \times 56.0 + 1.5 \times 7.0 = 77.7 \text{ kN/m} \quad (11.7)$$

Table 11.2: Load values and ULS verification of the central wall (per metre length).

Base of upper storey		
Dead: roof + wall	16.0 + 11.4	$G_k = 27.4 \text{ kN/m}$
Variable: roof		$Q_{k,roof} = 4.0 \text{ kN/m}$
ULS-a	$1.35 \times 27.4 + 1.5 \times 0 \times 4.0$	$= 37.0 \text{ kN/m}$
ULS-b	$1.2 \times 27.4 + 1.5 \times 4.0$	$= 38.9 \text{ kN/m}$
$N_{Ed} = 38.9 \text{ kN/m}$	U.C. = 38.9/390	$= 0.10$
Base of ground storey		
Dead: roof + floor + 2 walls	16.0 + 17.2 + 2 × 11.4	$G_k = 56.0 \text{ kN/m}$
Variable: floor (leading) + roof		$Q_{k,fl} = 7.0; Q_{k,roof} = 4.0$
ULS-a	$1.35 \times 56.0 + 1.5 \times 0.4 \times 7.0 + 1.5 \times 0 \times 4.0$	$= 79.8 \text{ kN/m}$
ULS-b	$1.2 \times 56.0 + 1.5 \times 7.0 + 1.5 \times 0 \times 4.0$	$= 77.7 \text{ kN/m}$
$N_{Ed} = 79.8 \text{ kN/m}$	U.C. = 79.8/390	$= 0.20$

so $N_{Ed} = 79.8 \text{ kN/m}$ and the unity check becomes

$$\frac{N_{Ed}}{N_{Rd}} = \frac{79.8}{390} = 0.20 \leq 1.0 \quad \checkmark \quad (11.8)$$

11.3.5. Extension to a three-storey building

The same wall is also verified for a three-storey variant of the building, with one additional storey and one additional floor slab. The building height then becomes approximately 8.3 m, so the assumption of negligible wind on the vertically loaded interior wall remains valid ($< 10 \text{ m}$). At the base of the ground-storey wall:

$$G_k = 16.0 + 2 \times 17.2 + 3 \times 11.4 = 84.6 \text{ kN/m}, \quad Q_{k,fl} = 2 \times 7.0 = 14.0 \text{ kN/m} \quad (11.9)$$

where no imposed-load reduction over storeys is applied (conservative). This gives:

$$N_{Ed,a} = 1.35 \times 84.6 + 1.5 \times 0.4 \times 14.0 = 122.6 \text{ kN/m} \quad (11.10)$$

$$N_{Ed,b} = 1.2 \times 84.6 + 1.5 \times 14.0 = 122.5 \text{ kN/m} \quad (11.11)$$

giving

$$\frac{N_{Ed}}{N_{Rd}} = \frac{122.6}{390} = 0.31 \leq 1.0 \quad \checkmark \quad (11.12)$$

A three-storey building on the same B4C4 wall also satisfies the Unity Check. Although the wall is very over dimensioned.

11.4. Concluding remarks

The verification shows that a two-storey and three-storey residential building on B4C4 walls is feasible with a very big margin. The Unity Checks suggests that more storeys could be carried before the unity check approaches 1.0. But when doing so, lateral actions (including wind, which can no longer be neglected above approximately 10 m building height), walls with openings, durability etc... should be verified. The thickness of the wall can also be decreased to achieve a more economical design.

Thesis discussion and Conclusion

This chapter brings together the findings of the literature study, the numerical investigations and the experimental results. Section 12.1 discusses the results on the basis of the four sub-questions formulated in Section 1.2. Subsequently, Section 12.2 provides an answer to the main research question.

As mentioned above, this thesis inverts the conventional order of the research process in which experiments normally precede numerical modeling. One of the research objectives formulated at the start of this thesis was to investigate whether this inverted (numerical – experimental – numerical) approach is a valid design strategy for the blocks. The starting point of this thesis was first of all of an experimental nature, with glass and earthcrete cubes being tested separately and combined (through single-bottle GBEBs) in the lab by Hoessein Alkisaie. After this, a finite element model of the GBEB was built using material parameters calibrated from the aforementioned experimental tests. By doing so, an iterative study was carried out, primarily on the tensile and compressive damage parameters of the earthcrete matrix and the glass bottles. These parameters were then transferred to the second phase of numerical modeling, which consisted of scaling the GBEB to a bigger unit containing multiple bottles (CGBEB). Once these simulations were completed, lab experiments were performed on a selected set of configurations. The loop was then closed with a third and final numerical phase, in which the models were recalibrated against the new experimental data.

The main value of carrying out the numerical part first is that the model acts as a design tool that can be used before the experimental phase, rather than merely as an explanation after the fact. Preliminary simulations indicated where failure would initiate within the blocks and how it would propagate, allowing for a more deliberate observation of the experimental fracture of the CGBEB under compressive loading. Closing the loop numerically then yields the most accurate result of the three phases, obtained more rapidly thanks to the knowledge gained from the earlier simulations.

However, the approach has clear drawbacks. The process is time-consuming, as it requires going back and forth between the experimental and numerical phases. Moreover, due to quasi-brittle size effects, the material properties of earthcrete do not transfer reliably to a large block with embedded geometry. Numerically, a multitude of parameters is available, and it is not always clear which parameter should be adjusted to improve the agreement with the experimental results.

In conclusion, the approach proved valid as a qualitative design strategy, where damage locations and their propagation were correctly identified, and the numerical results guided the experimental program. In a quantitative sense, however, its validity is limited: the transfer of material properties across scales led to an overestimation of the capacity, so the predicted peak loads were not accurate.

12.1. Thesis Discussion

12.1.1. First sub-question

“What configurations of glass bottles have been used in existing case studies as load-bearing wall components, and which configurations (existing or other) are most relevant for this research?”

From the case studies reviewed in Chapter 2 seven recurring configuration typologies can be distinguished: horizontal, vertical, diagonal, radial, alternating horizontal, checkered and mirrored. Horizontal placement of the bottles is the most common arrangement in practice, and the inter-bottle spacing is generally kept small to accommodate mortar placement. This recurrence is due to practical reasons: horizontally placed bottles are easier to stack on top of another and in most cases allow light transmission through the wall. The horizontal orientation is also structurally more favorable, as the compression tests by H. Alkisaie showed a higher capacity for this loading direction due to a more uniform transfer of stress and e.g. activation of hoop forces within the bottle. For these reasons, the horizontal configuration would have (in hindsight) been the most relevant one for this research.

Nevertheless, all simulations and experiments in this thesis were performed with vertically oriented bottles. The original planning included a progression from vertical to the horizontal orientation. However, this step proved unfeasible within the available time.

Rather than reproducing the above named field configurations on a larger scale, this research zoomed into a smaller section of a wall, translating them into a series of cubic blocks in which the two variables were varied independently: the number of embedded bottles (types B0 through B9) and the earthcrete cover, which is coupled to the inter-bottle spacing variable (variants C2, C4 and C6). To accommodate multiple bottles within one block, a block thickness of 240 mm was adopted. This parameterized numerical approach isolates the influence of bottle count and cover on the mechanical behavior of the blocks in a way that is more economical and less time-consuming but it comes with a clear limitation: the conclusions of this thesis apply strictly to axially loaded, vertically oriented bottles. No claim can be made that the results found here transfer to the horizontal configuration.

12.1.2. Second sub-question

“What are the key physical properties and mechanical behavior of the long beer glass bottle and the earthcrete mixture relevant for this research?”

Destructive compression tests performed at AGR in Delft on pre-damaged bottles yielded average axial fracture loads of 16.11 kN (line-simulated damage) and 17.30 kN (manual abrasion). Undamaged bottles tested axially reached an average fracture load of approximately 42.8 kN, more than twice that of the damaged bottles. In both the physical tests and the simulations, failure initiates at the shoulder, where the curved geometry of the bottle converts axial compression into bending, producing rings of tensile principal stress. The bottle's outer surface is thus highly sensitive to flaws: scratches and imperfections act as stress concentrators at which tensile stress is locally intensified. The governing parameter for failure is thus the density and severity of the flaws on the shoulder surface. This also explains why, in the block experiments of Chapter 9, the heels and shoulders of the embedded bottles were pulverized despite being confined by the matrix. It should be noted that only undamaged bottles were used in the block tests. In a real application, walls would more likely be built with reused bottles, which would not reach the undamaged mean strength.

The yield stress of glass is mesh dependent: the same experimental fracture load is matched by 37 MPa on a 5 mm mesh but only 26 MPa on a 10 mm mesh (Section 8.2). The reason for this is that the numerically dissipated energy scales with the size of the element where the crack occurs, so a coarser mesh must be compensated for by a lower strength to dissipate the same energy at the same load. Therefore, these values must be understood as mesh-specific calibration parameters rather than material properties, and they require recalibration for any change in mesh size. Once the bottle was embedded in the earthcrete matrix, the tensile strength had to be reduced even further, to 3.7 MPa, to approximate the experimental response. This reduction should also not be read as a material effect. Because the glass

is stiffer than the matrix, it attracts a larger share of the load, and lowering its strength compensates for this effect.

During this investigation, multiple simulations were conducted to assess the influence of various parameters on the results. Increasing the tensile damage parameter while keeping the compressive damage constant resulted in a more brittle post-peak response. Conversely, reducing the tensile damage yielded a more ductile behavior after the initial fracture. The reverse scenario (maintaining the tensile damage at a high value while varying the compressive damage) had little effect on the overall response of the glass bottle. Based on these findings, for glass embedded within earthcrete, the initial damage values of c50% and t99% were adopted. After experimental testing of the block however, the compressive damage was increased further so that the glass would not transfer a disproportionate amount of load after fracture.

The earthcrete used in this research is a self-compacting, cement-based mortar composed of natural soil, CEM I 52.5 R, water and PCE superplasticiser (Table 9.1). Its relevant mechanical characteristics are a low compressive strength of the order of a few MPa, quasi-brittle softening behavior, and a relatively large fracture process zone, which makes the CDP model a suitable constitutive choice. The property values adopted from H. Alkisaie for a 10 mm mesh, however, proved inadequate for the CGBEB models: this became apparent midway through the B0–B9 simulation series, but the original values were still used for the ensuing configurations to preserve uniformity, so that the configurations could be compared with one another. Afterwards, two CGBEB simulations run with the updated values (the merged versus unmerged geometry comparison) showed that these, too, overestimated the response. This is possibly due to size effects and difference in proportions. After the experimental tests on the cubic blocks, a recalibration campaign with multiple iterations was therefore carried out to approximate the experimental results numerically.

Finally, the glass–earthcrete interface warrants discussion. It was initially treated as a property of secondary importance, and the numerical models assumed a fully bonded or merged interface in the majority of cases. One exploratory simulation with a cohesive interface, using the literature-based bond strength and debonding energy (Appendix H), lowered the peak capacity relative to the merged model and relocated the bottle damage toward the bearing regions at the neck and heel. The fully bonded model thus contributes to the over-prediction of the composite capacity. A sensitivity study on these parameters, however, remains future work (Chapter 13). The only available experimental reference for glass–cementitious debonding suggests a bond strength below 1 MPa and a very low debonding energy, obtained moreover from borosilicate rather than soda-lime glass, while commercial bottles additionally carry a polyethylene cold-end coating that can be expected to reduce the bond strength further. The interface is thus the least characterized component of the composite, and in hindsight a more influential one than initially assumed.

12.1.3. Third sub-question

“How do different block configurations perform (maximum loads and failure behavior) under compressive loading, as evaluated through Finite Element Modeling (FEM) and experimental testing?”

Numerical performance. In the simulations (Chapter 8), all configurations share an initial elastic region up to a displacement of approximately 0.945 mm, and the axial stiffness of the block increases with the number of embedded bottles, reflecting the higher stiffness of glass relative to earthcrete. The nine-bottle block B9C2 attained the highest simulated peak load (806.92 kN) but displayed a more brittle post-peak response, which reduces confidence in its value. Among the B0–B5 types, B4C4 performed best. An earthcrete cover of 2 cm was found to lower capacity, with tensile damage localizing at the corners of the block, whereas the 4 cm and 6 cm covers performed similarly, with the 6 cm variant offering minimal additional benefit. The simulated damage sequence is consistent across configurations: glass fracture initiates at the bottle shoulder at the end of the elastic branch, after which tensile damage propagates into the surrounding matrix upon which the response becomes inelastic.

Why the model and the experiments disagree. The comparison in Table 9.2 makes up the central result of this thesis, and it is a negative one for the model as calibrated: the simulations over-predict the experimental peak loads by 42.5% (B0C0), 103.9% (B5C4) and 124.8% (B4C4). The over-prediction of the plain block (42.5%) stems from the earthcrete model itself. A calibration at prism scale therefore overestimates block-scale strength, whereas the much larger over-prediction of the glass-containing blocks is likely to stem from how the model treats the bottles.

Experimentally, four to five bottles cost 13–18% of capacity, slightly reduce stiffness and embrittles the post-peak response. Numerically, adding bottles increases both stiffness and capacity. The fully bonded interface makes the model behave as a true composite and the much stiffer glass attracts more load. As a consequence, both the predicted stiffness and the predicted capacity is raised with every added bottle.

Why B5C4 slightly outperformed B4C4, experimentally. The compression tests (Chapter 9) showed that all three tested configurations (B0, B4 and B5) follow a linear-elastic rise to approximately 220 kN. The plain block B0C0 reached the highest average peak load of 401.27 kN and exhibited the most ductile post-peak response. The glass-containing blocks reached 329.81 kN (B4C4) and 348.82 kN (B5C4) and the response became more brittle in the post peak stage which is an unfavorable trait for structural elements, where post-peak ductility provides warning of failure and allows stress redistribution. The slight advantage of B5C4 over B4C4 suggests a mildly beneficial role of the central bottle: with five bottles, load redistribution among the containers is more effective, so premature fracture of a single early-loaded bottle is less consequential than in the four-bottle layout. Given the sample size, however, this difference cannot be separated from experimental scatter. The stiffness of both glass-containing types was slightly below that of B0C0: although glass itself is much stiffer than earthcrete, the unutilized internal voids the bottles create cancel this advantage, and the stresses redistribute mainly through the matrix. During testing, vertical splitting cracks initiated near the cube edges and wedge-shaped fragments detached progressively in all configurations, with the glass-containing specimens showing a higher density of vertical fracture lines where the cover is thinnest.

12.1.4. Fourth sub-question

“Which bottle configurations offer the best trade-off between maximizing the number of embedded bottles and limiting the loss of load-bearing capacity and buildability of the wall element?”

The experiments show that embedding bottles does not strengthen the block: the presence of four to five bottles costs 13–18% of peak capacity relative to the plain block, while lowering the stiffness slightly. The interbottle-spacing variable is of secondary relevance. Some take-aways are: first, very thin covers should be avoided: the 2 cm variant showed both reduced numerical capacity and unfavorable damage localization at block corners, while increasing the cover beyond 4 cm did not benefit.

A central bottle appears mildly favorable for the internal load distribution, as suggested by B5C4 outperforming B4C4 experimentally, although this should be confirmed with larger sample sizes.

Densely packed configurations of the B9 type are unattractive in the vertical orientation despite their high simulated peak load: their predicted post-peak behavior is brittle, and, as noted in Section 9.6, the narrow gaps between bottles make void-free pouring unfeasible.

According to the experimental results, configuration B5C4 with five bottles represents the best available compromise at block level: it embeds the most glass among the tested configurations, respects the 4 cm cover threshold, remains castable, and its central bottle appears to improve internal load redistribution rather than degrade it.

12.2. Thesis Conclusion

The main research question of this thesis was:

“What is the influence of different bottle configurations on the mechanical behavior of earth-crete wall elements embedded with long-neck glass bottles?”

On the basis of the investigations, this question is answered below, separated into the experimental and the numerical findings.

12.2.1. Experimental conclusions

1. **The dominant influence is the bottle-count** Embedding four to five vertically oriented bottles in a 240 mm cubic earthcrete block reduces the peak compressive capacity by 13–18% (from 401.27 kN for the plain block to 329.81–348.82 kN), slightly lowers the initial stiffness and makes the post-peak response distinctly more brittle. Differences among the glass-containing B4 and B5 configurations are small but a central bottle appears mildly favorable, possibly because of a more effective load redistribution among the bottles.
2. **The blocks retain substantial load-bearing capacity.** Even the weakest tested configuration carried a nominal stress of approximately 5.7 MPa over the gross cross-section (7.0 MPa for the plain block), which supports the construction of multi-storey buildings.

12.2.2. Numerical conclusions

1. **Earthcrete cover effects are secondary but not negligible.** A minimum earthcrete cover of approximately 4 cm should be respected: thin (2 cm) covers reduce capacity and concentrate damage near the corners, and the fracture patterns localize where the cover is thinnest, while covers beyond 4 cm bring no additional benefit.
2. **The fully bonded CDP model is qualitatively informative but quantitatively unvalidated for the composite blocks.** It reproduces the observed damage sequence: shoulder-initiated glass fracture followed by matrix damage and wedge-type failure but may not be transferrable for larger wall units.
3. **Recalibration improves but does not validate.** Model 14_03 reproduces the plain block; the combination of earthcrete model 14_02 with the strongly reduced glass properties G_4 (tensile strength 3.714 MPa) and 90% compressive damage is the most predictive found for the composite blocks, yet remains a fit rather than a validation.

In summary, glass bottles embedded in earthcrete should be understood not as reinforcement but as functional voids. For a slight decrease in the amount of compressive capacity, they reduce the volume of earthcrete required, divert waste glass from disposal, and allow light to pass through the wall (when positioned horizontally). The value of the glass-bottle-embedded earthcrete block is therefore economic and environmental rather than structural.

13

Research recommendations

This chapter suggests several recommendations to advance research on this topic.

13.1. Recommendations Numerical Regime

Inverted approach of the workflow

Shortening the workflow. Although the inverted approach proved valuable as a design tool, it introduces uncertainties when the geometry is scaled or altered. For this reason, a set of plain cubic blocks (CGBEB type B0) should ideally have been tested (in the lab) at the start of the workflow, alongside Alkisaie's GBEB tests. With both these experimental data sets of prism and block, the calibrated material properties of the two geometries could have been compared directly. Additionally, the size effect could have been quantified as a scale factor on the stress–strain input values. This would have made the numerical phase more accurate from the beginning. The final recalibration phase could have thereby been reduced or even been rendered unnecessary, shortening thus the overall workflow.

Improvements to the numerical model

Element type. With first-order C3D4 tetrahedra at a 5–10 mm global mesh, at most one element spans the approximately 3.4 mm bottle wall, so the bending stresses that govern shoulder failure are not represented well. The C3D4 is in fact notoriously stiff and poor at capturing stress concentrations [1]. A possible solution would be to mesh the bottle with second-order 10-node tetrahedral solid elements (C3D10), accepting the computational cost through local mesh refinement (with a coarser mesh towards the lateral faces of the block).

Recalibrate on the full experimental set with 5 mm mesh. The material model for earthcrete and glass should be fitted against one configuration (e.g. B4C4) and validated blind against the remaining configurations. For a more accurate result, the mesh would need to be decreased from 10 mm to 5 mm.

Computing stresses by dividing F by the net cross-section of the block B4C4 In Appendix J the stresses were computed by dividing the forces from the experimental data with the gross cross-section of the block ($240 \times 240 \text{ mm}^2$). Although this is a good practice for B0C0, for B4C4 stresses should be computed using the net cross-section at mid-height, obtained by subtracting the block area by the hollow interior area of the 4 bottles.

Prematurely aborted simulations A recurring problem during this thesis was that some simulations aborted prematurely. The cause for this error lies likely in the very high (99%) assigned values for the maximum tensile and compression damage. Numerically, the damaged elements retain only 1% of their elastic stiffness and can distort excessively until they invert (or attain a negative volume). At this

point, Abaqus/Explicit terminates the analysis. To mitigate this, the maximum tensile damage should be capped at 95-98% instead of 99%. In this case, the residual stiffness makes the elements extremely soft but numerically it prevents the elements from collapsing (or attaining a negative volume). Another option is to enable element deletion before inversion.

Characterisation of the interface

Measure the bottle–matrix bond. A pull-out test on glass cast with a polyethylene cold-end coating into earthcrete cylinders would provide more accurate values for the bond strength and debonding energy required by the numerical model.

Carry out a sensitivity analysis for the glass–earthcrete interface. The fully bonded interface assumption most likely one of the contributors to the model's over-prediction of the composite capacity. It is recommended in further research to replace the merged (fully bonded) interface by a surface-based cohesive contact formulation, with the bond strength and debonding energy as input parameters. Given the very low bond strength values reported in the literature for glass–cementitious interfaces, a sensitivity study with range from near-zero bond to the literature values should be carried out, extending the exploratory simulation of Appendix H.

13.2. Recommendations Experimental Regime

Testing

Test the untested configurations. Tests on at least one thin-cover variant (B4C2) and one high-count variant (B9C2), would establish whether the configuration effects predicted numerically, reflect the experimental tests. And also to investigate what effects it has on the stiffness of the block and possibly confirm the higher brittleness with higher bottle-count.

Test horizontally oriented bottles. All experiments in this thesis use vertically oriented bottles, whereas built practice predominantly places bottles horizontally. Horizontal orientation changes the load path, with the load being carried across the body rather than along its axis. A horizontal test series on the same block geometry is the most important experimental extension of this research.

Assess durability and thermal performance. For an earthen material intended for housing long-term creep under sustained load merit investigation. The embedded air volume may also contribute a measurable thermal insulating benefit. It would be interesting to research thermal performance with bottle count variation provided the containers are properly sealed.

Fabrication

Improve bottle fixation during casting. As noted in Section 9.6, the string-and-bead system occasionally failed when the buoyant force of the bottles exceeded the adhesive's grip. Grooves in the mold allowing the string to seat deeper, mechanical fixation of the string with screws, and single-use or cleanable tensioning elements are recommended. Alternatively, spacer clips bearing on the mold walls, comparable to rebar spacers, would also be a good option.

Use of Fly Ash in the mixture Fly ash can be added to the earthcrete mixture to help improve its strength and workability. Another main benefit of incorporating fly ash into the mixture is that it reduces carbon dioxide emissions. For every ton of cement replaced with fly ash, about one ton of emissions is avoided.

Building block in a larger context

Investigate the larger building units. A wall is not a stack of isolated blocks: usually earthcrete is used in a monolithic manner with lateral constraints. This will influence load distribution in ways the single-block tests cannot reveal. Small masonry assemblages (two- to three-block prisms wide) are the recommended next experimental step.

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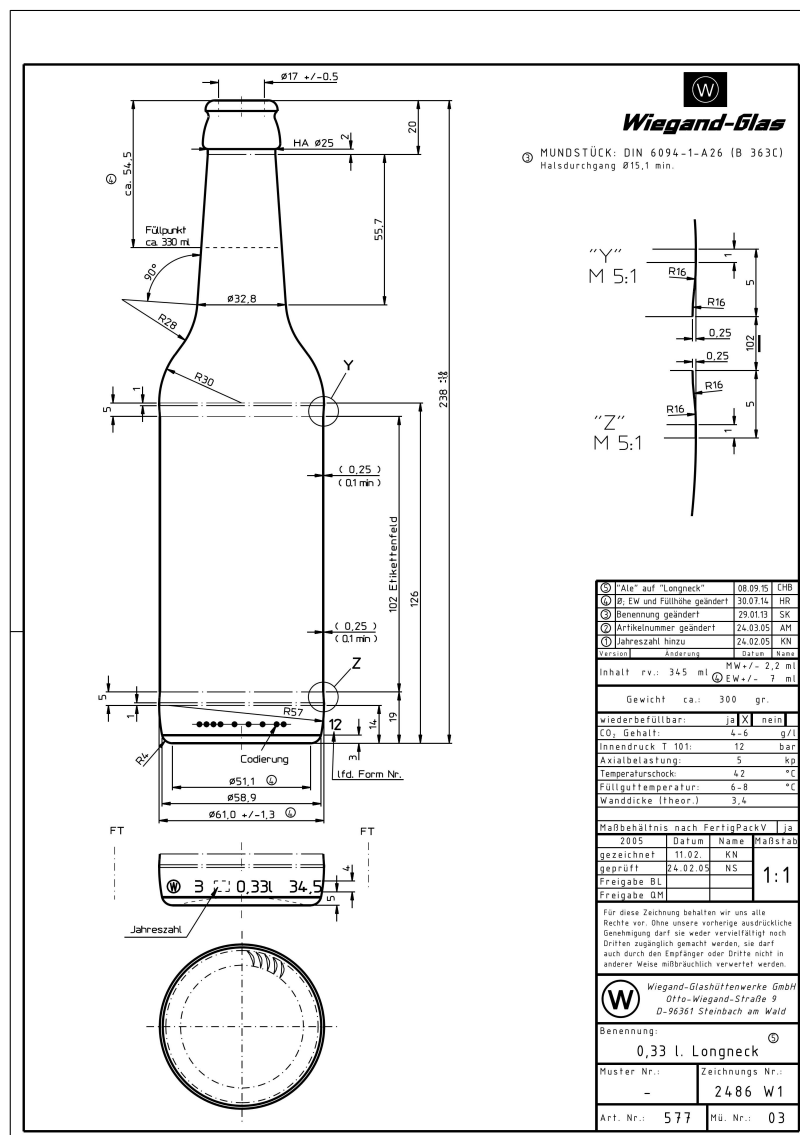
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A

Brouwland beer bottle specifications



B

AGR Measurements

Sample set description		Heel height: 13.8 mm; Body height: 67.7 mm; Shoulder height: 127.5 mm; BS: 2.13 mm; Neck height: 176.8 mm; Diameter upper neck (height: 198.5 mm): 27.87 mm; Diameter lower neck (height: 163 mm): 31.04 mm											
Sample nr.	Cavity nr.	Height in mm		Diameter shoulder in mm		Diameter heel in mm		Diameter body in mm		Finish A/E diameter in mm		Finish B/T diameter in mm	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
1	40	238.09	238.05	60.17	60.84	60.37	60.54						
2	17	238.03	238.19	60.09	60.37	60.30	60.77						
3	24	238.00	238.16	60.14	60.54	60.38	60.55						
4	50	238.05	238.32	60.25	60.76	60.41	60.62						
5	53	237.97	238.12	60.12	60.71	60.24	60.92						
6	5	238.10	238.22	60.29	60.45	60.38	60.59						
7	47	237.97	238.14	60.14	60.73	60.35	60.81						
8	47	237.87	238.14	60.13	60.64	60.32	60.90						
9	2	237.94	238.15	60.35	60.57	60.43	60.60						
10	14	237.80	237.94	60.16	60.56	60.26	60.68	59.08	59.92	26.38	26.46	28.33	28.72
Average		237.98	238.14	60.18	60.62	60.34	60.70	59.08	59.92	26.38	26.46	28.33	28.72

Figure B.1: Dimensional measurements of glass bottles. Data by Clarissa Justino de Lima on 01/03/2022 [33]

Sample nr.	Cavity nr.	Neck thickness in mm		Shoulder thickness in mm		Shoulder contact thickness in mm		Mid-sidewall thickness in mm		Heel contact thickness in mm		Lower most heel thickness in mm		Bearing surface thickness in mm		Value
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
1	2	3.09	3.74	2.46	3.07	2.24	2.70	2.75	3.42	2.76	3.38	2.68	3.29	4.58	6.06	5.94
2	47	3.15	4.45	2.36	3.13	2.20	3.12	2.68	3.40	2.55	2.97	2.50	2.90	4.56	5.51	5.56
3	14	3.02	3.49	2.18	2.76	2.14	2.73	3.38	3.71	2.75	3.58	2.68	3.77	4.74	6.38	6.00
Min. of samples		3.02		2.18		2.14		2.68		2.55		2.50		4.56		5.56
Max. of samples		4.45		3.13		3.12		3.71		3.58		3.77		6.38		6.00
Average		3.49		2.66		2.52		3.22		3.00		2.97		5.31		5.83

Figure B.2: Thickness measurements of glass bottles. Data provided by Clarissa Justino de Lima on 25/02/2022 [33]

Sample set	Sample nrs.	Cavity nrs.	Sample Arrangement		Test Condition	Tilt Angle in degrees θ	Coefficient of Friction $\tan(\theta)$
			Bottom	Top			
1	1-2-3	Sample 1: 40	2-3	1	DRY	10	0.176
		Sample 2: 17	3-1	2	DRY	10.5	0.185
		Sample 3: 24	1-2	3	DRY	9.5	0.167
Average						10	0.176

Figure B.3: Tilt table measurements of glass bottles. Data provided by Clarissa Justino de Lima on 01/03/2022 [33]

Bottle conditioning	5 min line simulation, line-sim (tape marked with pink ink)			
Sample set description	33 cl amber bottles, line-simulated by Laura and Clarissa on 23/02/2022			
Sample nr.	Cavity nr.	Vertical load at fracture		Origin Location
		kg_f	kN	
1	21	1825	17.90	Shoulder Contact
2	53	1790	17.56	Shoulder Contact
3	41	1835	18.00	Shoulder Contact
4	26	1865	18.30	Shoulder Contact
5	17	1885	18.49	Heel Contact
6	40	1460	14.32	Shoulder Contact
7	25	1555	15.25	Shoulder Contact
8	30	1450	14.22	Shoulder Contact
9	32	1845	18.10	Heel Contact
10	15	1360	13.34	Heel Contact
11	52	1025	10.06	Shoulder Contact
12	34	1495	14.67	Shoulder Contact
13	5	Nb (> 2050)	20.11	No Break
14	32	1545	15.16	Shoulder Contact
15	12	1770	17.36	Shoulder Contact
16	27	1815	17.80	Shoulder Contact
17	16	1765	17.31	Shoulder Contact
18	31	1795	17.61	Shoulder Contact
19	16	1870	18.34	Shoulder Contact
20	48	1015	9.96	Heel Contact
21	23	1970	19.33	Shoulder Contact
22	43	1970	19.33	Shoulder Contact
23	9	1670	16.38	Shoulder Contact
24	25	1560	15.30	Shoulder Contact
25	43	1590	15.60	Shoulder Contact
26	33	1155	11.33	Shoulder Contact
27	33	1630	15.99	Shoulder Contact
28	27	1430	14.03	Shoulder Contact

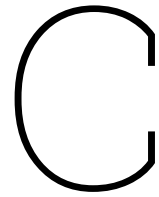
Figure B.4: Vertical load fractures data of line-simulated glass bottles [33]

Bottle conditioning	Abraded with 150 grit emery paper, shoulder and heel contact regions (blue ink)			
Sample set description	33 cl amber bottles, abraded by Younes Maachi on 23/02/2022			
Sample nr.	Cavity nr.	Vertical load at fracture		Origin Location
		kg_f	kN	
1	41	1820	17.85	Heel Contact
2	32	1390	13.64	Shoulder Contact
3	45	1410	13.83	Shoulder Contact
4	26	1900	18.64	Shoulder Contact
5	6	1355	13.29	Shoulder Contact
6	5	2050	20.11	Heel Contact
7	27	1725	16.92	Shoulder Contact
8	9	2040	20.01	Shoulder Contact
9	33	Nb (> 2050)	Nb (> 20.11)	No Break
10	12	1515	14.86	Shoulder Contact
11	37	1370	13.44	Shoulder Contact
12	50	1950	19.13	Shoulder Contact
13	52	1890	18.54	Shoulder Contact
14	16	2050	20.11	Shoulder Contact
15	37	1845	18.10	Heel Contact
16	3	1835	18.00	Shoulder Contact
17	5	1740	17.07	Shoulder Contact
18	23	1595	15.65	Shoulder Contact
19	17	2045	20.06	Heel Contact
20	13	1855	18.20	Shoulder Contact
21	23	1690	16.58	Shoulder Contact
22	47	2045	20.06	Heel Contact
23	21	1725	16.92	Shoulder Contact
24	9	1140	11.18	Heel Contact
25	24	1675	16.43	Shoulder Contact
26	21	1630	15.99	Shoulder Contact
27	32	Nb (> 2050)	Nb (> 20.11)	No Break
28	45	2000	19.62	Shoulder Contact

Figure B.5: Vertical load fractures data of manually glass bottles [33]

APPROXIMATE TENSILE BREAKING STRESSES OF SODA LIME GLASS (psi)																									
psi																									
SURFACE CONDITION	<1ms	1s	2s	3s	5s	10s	15s	20s	30s	1min	5min	10min	15min	20min	30min	1hr	10hr	12hr	1day	3day	1wk	long			
Pristine inside BB	#####	#####	95250	92250	88500	84000	81750	80250	78000	75000	68250	66750	65250	63750	62250	60000	54750	53250	51750	50250	48000	45000			
Pristine inside PB	40000	26800	25400	24600	23600	22400	21800	21400	20800	20000	18200	17800	17400	17000	16600	16000	14600	14200	13800	13400	12800	12000			
Flute valley OW	24462	16390	15533	15044	14433	13699	13332	13087	12720	12231	11130	10886	10641	10396	10152	9785	8929	8684	8439	8195	7828	7339			
Mild abrasions	20000	13500	12700	12300	11800	11200	10900	10700	10400	10000	9100	8900	8700	8500	8300	8000	7300	7100	6900	6700	6400	6000			
Flute valley RT	16390	10981	10408	10080	9670	9178	8933	8769	8523	8195	7457	7294	7130	6966	6802	6556	5982	5818	5655	5491	5245	4917			
Mild abr OW	10000	6750	6350	6150	5900	5600	5450	5350	5200	5000	4550	4450	4350	4250	4150	4000	3650	3550	3450	3350	3200	3000			
Moderate abr OW	8000	5400	5080	4920	4720	4480	4360	4280	4160	4000	3640	3560	3480	3400	3320	3200	2920	2840	2760	2680	2560	2500			
Mod Sev abr RT	6700	4500	4254	4120	3953	3752	3651	3584	3484	3350	3048	2981	2914	2850	2780	2680	2445	2378	2311	2244	2144	2250			
Severe abrasions	5000	3350	3175	3075	2950	2800	2725	2675	2600	2500	2275	2225	2175	2125	2075	2000	1825	1775	1725	1675	1600	1700			
Deep bruises	3000	2000	1905	1845	1770	1680	1635	1605	1560	1500	1365	1335	1305	1275	1245	1200	1095	1065	1035	1005	960	650			
Cracks	1500	1000	952	922	885	840	817	802	780	750	682	667	652	640	622	600	547	532	517	502	480	470			
kg/cm2																									
SURFACE CONDITION	<1ms	1s	2s	3s	5s	10s	15s	20s	30s	1min	5min	10min	15min	20min	30min	1hr	10hr	12hr	1day	3day	1wk	long			
	Impact	Crowning		Thermal						Pressure testing					Post-tensioner							Warehouse			
Pristine inside BB- inside surfa	10546	7066	6697	6486	6222	5906	5748	5642	5484	5273	4798	4693	4588	4482	4377	4218	3849	3744	3638	3533	3375	3164			
Pristine inside PB- inside surfa	2812	1884	1786	1730	1659	1575	1533	1505	1462	1406	1280	1251	1223	1195	1167	1125	1026	998	970	942	900	844			
Flute valley OW- region betwee	1720	1152	1092	1058	1015	963	937	920	894	860	783	765	748	731	714	688	628	611	593	576	550	516			
Mild abrasions- bottle just fab	1406	949	893	865	830	787	766	752	731	703	640	626	612	598	584	562	513	499	485	471	450	422			
Flute valley RT- between flutes	1152	772	732	709	680	645	628	616	599	576	524	513	501	490	478	461	421	409	398	386	369	346			
Mild abr OW- Strength compara	703	475	446	432	415	394	383	376	366	352	320	313	306	299	292	281	257	250	243	236	225	211			
Moderate abr OW- Strength com	562	380	357	346	332	315	307	301	292	281	256	250	245	239	233	225	205	200	194	188	180	176			
Mod Sev abr RT- Strength of a re	471	316	299	290	278	264	257	252	245	236	214	210	205	200	195	188	172	167	163	158	151	158			
Severe abrasions	352	236	223	216	207	197	192	188	183	176	160	156	153	149	146	141	128	125	121	118	112	120			
Deep bruises	211	141	134	130	124	118	115	113	110	105	96	94	92	90	88	84	77	75	73	71	67	46			
Cracks	105	70	67	65	62	59	57	56	55	53	48	47	46	45	44	42	38	37	36	35	34	33			
Mega Pascal																									
SURFACE CONDITION	<1ms	1s	2s	3s	5s	10s	15s	20s	30s	1min	5min	10min	15min	20min	30min	1hr	10hr	12hr	1day	3day	1wk	long			
Pristine inside BB	1034.2	692.9	656.7	636.0	610.2	579.2	563.6	553.3	537.8	517.1	470.6	460.2	449.9	439.5	429.2	413.7	377.5	367.1	356.8	346.5	330.9	310.3			
Pristine inside PB	275.8	184.8	175.1	169.6	162.7	154.4	150.3	147.5	143.4	137.9	125.5	122.7	120.0	117.2	114.5	110.3	100.7	97.9	95.1	92.4	88.3	82.7			
Flute valley OW	168.7	113.0	107.1	103.7	99.5	94.4	91.9	90.2	87.7	84.3	76.7	75.1	73.4	71.7	70.0	67.5	61.6	59.9	58.2	56.5	54.0	50.6			
Mild abrasions	137.9	93.1	87.6	84.8	81.4	77.2	75.2	73.8	71.7	68.9	62.7	61.4	60.0	58.6	57.2	55.2	50.3	49.0	47.6	46.2	44.1	41.4			
Flute valley RT	113.0	75.7	71.8	69.5	66.7	63.3	61.6	60.5	58.8	56.5	51.4	50.3	49.2	48.0	46.9	45.2	41.2	40.1	39.0	37.9	36.2	33.9			
Mild abr OW	68.9	46.5	43.8	42.4	40.7	38.6	37.6	36.9	35.9	34.5	31.4	30.7	30.0	29.3	28.6	27.6	25.2	24.5	23.8	23.1	22.1	20.7			
Moderate abr OW	55.2	37.2	35.0	33.9	32.5	30.9	30.1	29.5	28.7	27.6	25.1	24.5	24.0	23.4	22.9	22.1	20.1	19.6	19.0	18.5	17.7	17.2			
Mod Sev abr RT	46.2	31.0	29.3	28.4	27.3	25.9	25.2	24.7	24.0	23.1	21.0	20.6	20.1	19.7	19.2	18.5	16.9	16.4	15.9	15.5	14.8	15.5			
Severe abrasions	34.5	23.1	21.9	21.2	20.3	19.3	18.8	18.4	17.9	17.2	15.7	15.3	15.0	14.7	14.3	13.8	12.6	12.2	11.9	11.5	11.0	11.7			
Deep bruises	20.7	13.8	13.1	12.7	12.2	11.6	11.3	11.1	10.8	10.3	9.4	9.2	9.0	8.8	8.6	8.3	7.5	7.3	7.1	6.9	6.6	4.5			
Cracks	10.3	6.9	6.6	6.4	6.1	5.8	5.6	5.5	5.4	5.2	4.7	4.6	4.5	4.4	4.3	4.1	3.8	3.7	3.6	3.5	3.3	3.2			

Figure B.6: Approximate tensile breaking stresses of soda lime glass containers (psi) [24]



Numerical results with Bottle A

C.1. Solid vs. shell elements

Shell elements were considered for the bottle in the early stages of the modeling, as they are typically used for thin-walled structures. However, this approach was not pursued for two reasons. First, the wall thickness of the bottle varies considerably along its height, so the shell would have to be partitioned into sections, each with its own assigned thickness, whereas a solid geometry captures the variation directly. And in the trial models, the connections between shell sections of different thickness produced persistent numerical errors that could not be resolved. Solid elements avoid this issue at the cost of the through-thickness being spanned by a single C3D4 element, which is known to behave overly stiff in bending. This limitation is accounted for in the interpretation of the results (Section 11.1.3).

C.2. Crack pattern of bottle A with concave bottom

When the bottle is modeled with a concave base in Abaqus according to the specifications in Appendix A, the first fracture consistently occurs at that location instead of at the shoulder. Two factors contribute to this. First, the modeled concave base produces an irregular mesh of reduced quality in that region. Second, the flat ring on which the bottle rests concentrates the contact with the base plate into a small area. As a consequence, high stresses are produced. In reality, this ring carries knurls that distribute the contact, but at the adopted mesh size they could not be represented in the model. Given this geometric discrepancy and reduced mesh quality, the concave bottle was later on replaced by a flat bottom.

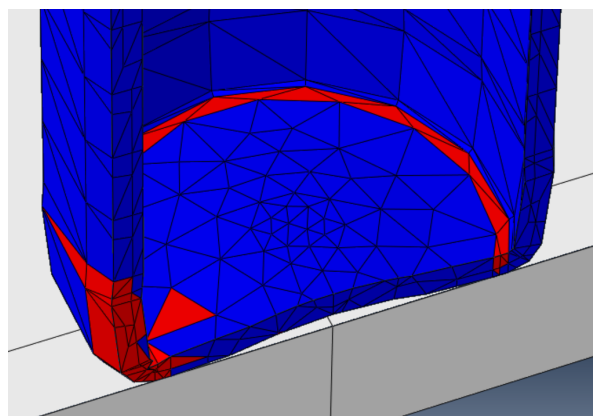


Figure C.1: Tensile damage at the heel of Bottle A (concave geometry)

C.3. Bottle A in the GBEB

Once the glass bottle type A (series P) is embedded in the GBEB, both the capacity and the post-peak behavior differ significantly from those of model [GBEB 6m - 37MPa | 50%/99%]. This difference is partly due to the incorrect earthcrete material parameters. The large load drops, however, are caused by the glass which is considerably stiffer than the earthcrete. It attracts the majority of the load as the matrix is compressed, and each fracture of the glass therefore releases a large share of the total load at once. After the glass has fractured, the slope of the F–u curve is also reduced, indicating that the load is subsequently carried by the earthcrete alone.

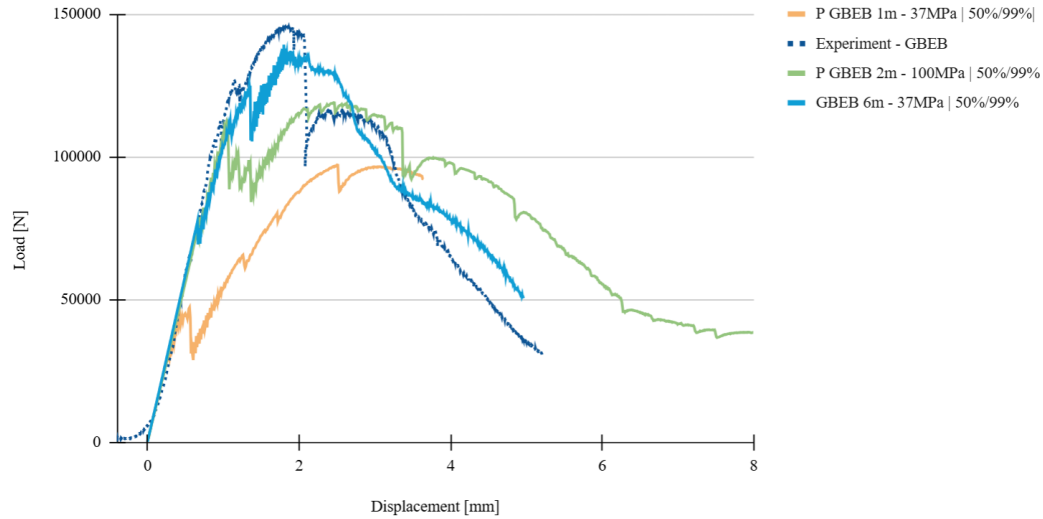


Figure C.2: GBEB with Bottle A (series P) vs. Bottle B

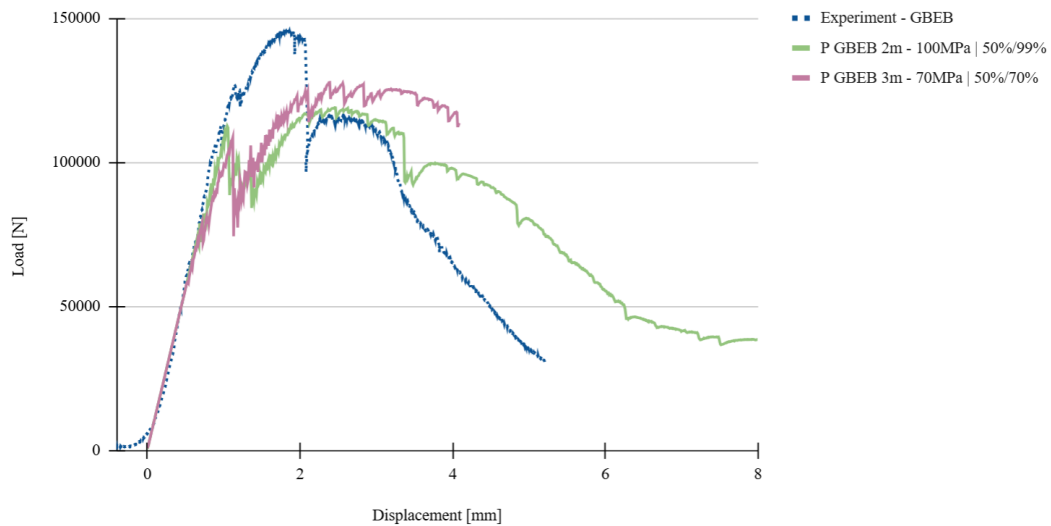


Figure C.3: Changing the tensile strength of Bottle A to 70 MPa and tensile damage to 70% relative to [P GBEB 2m - 100MPa | 50%/99%]

D

Damage evolution of model [07_02_GBEB_5mm_CDP_EC32]

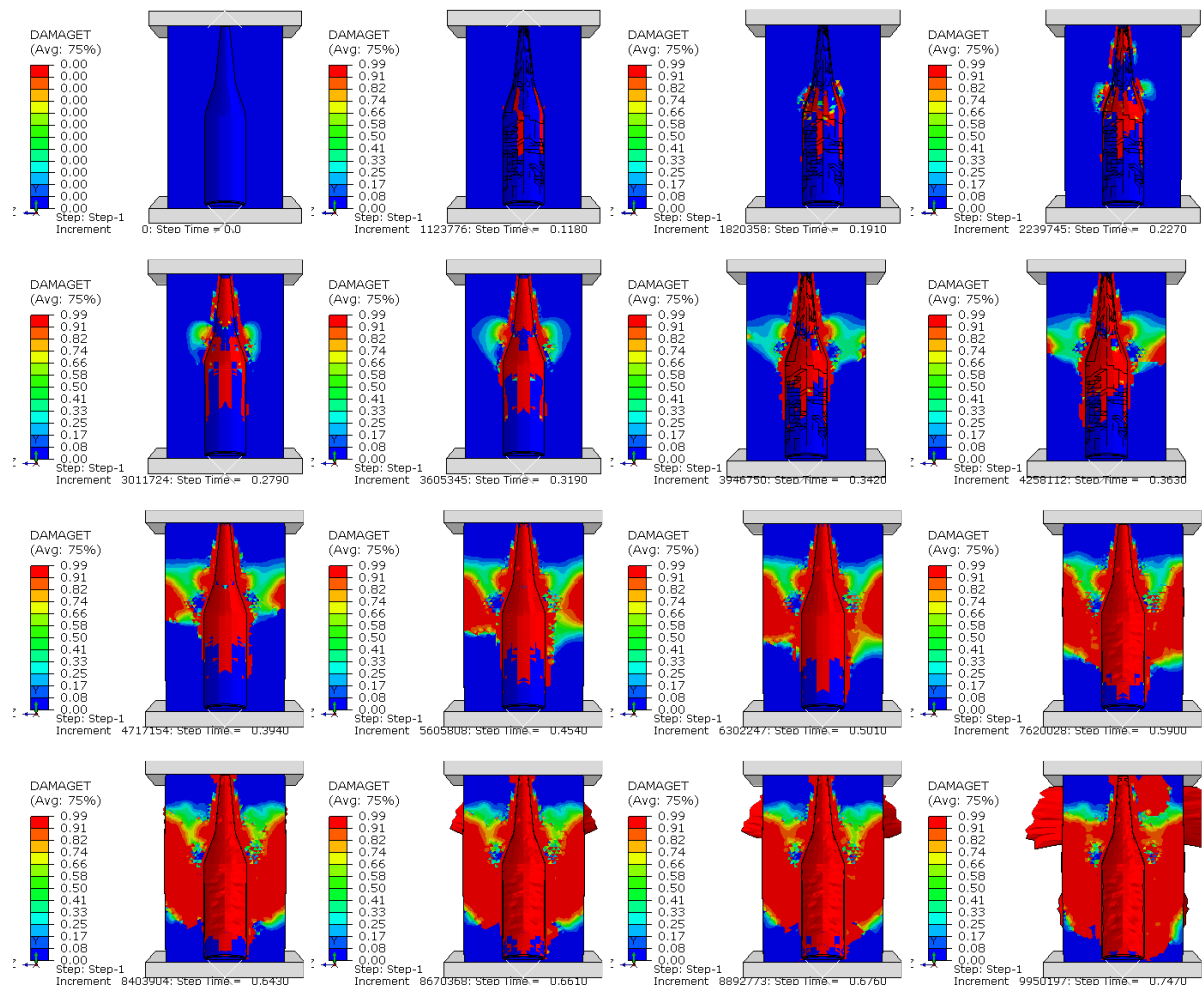


Figure D.1: DAMAGET of GBEB model [07_02_GBEB_5mm_CDP_EC32]

E

FEM simulations B4C4

E.1. Tensile damage of the B4 series

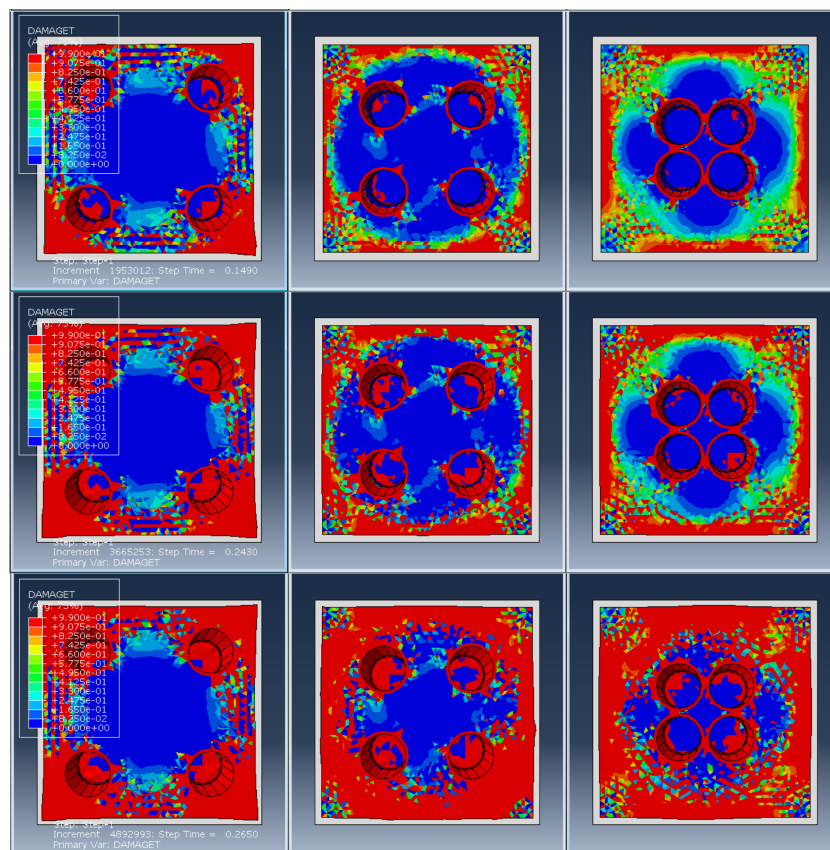


Figure E.2: DAMAGET of CGBEB type B4. B4C2 (left) B4C4 (middle) and B4C6 (right)

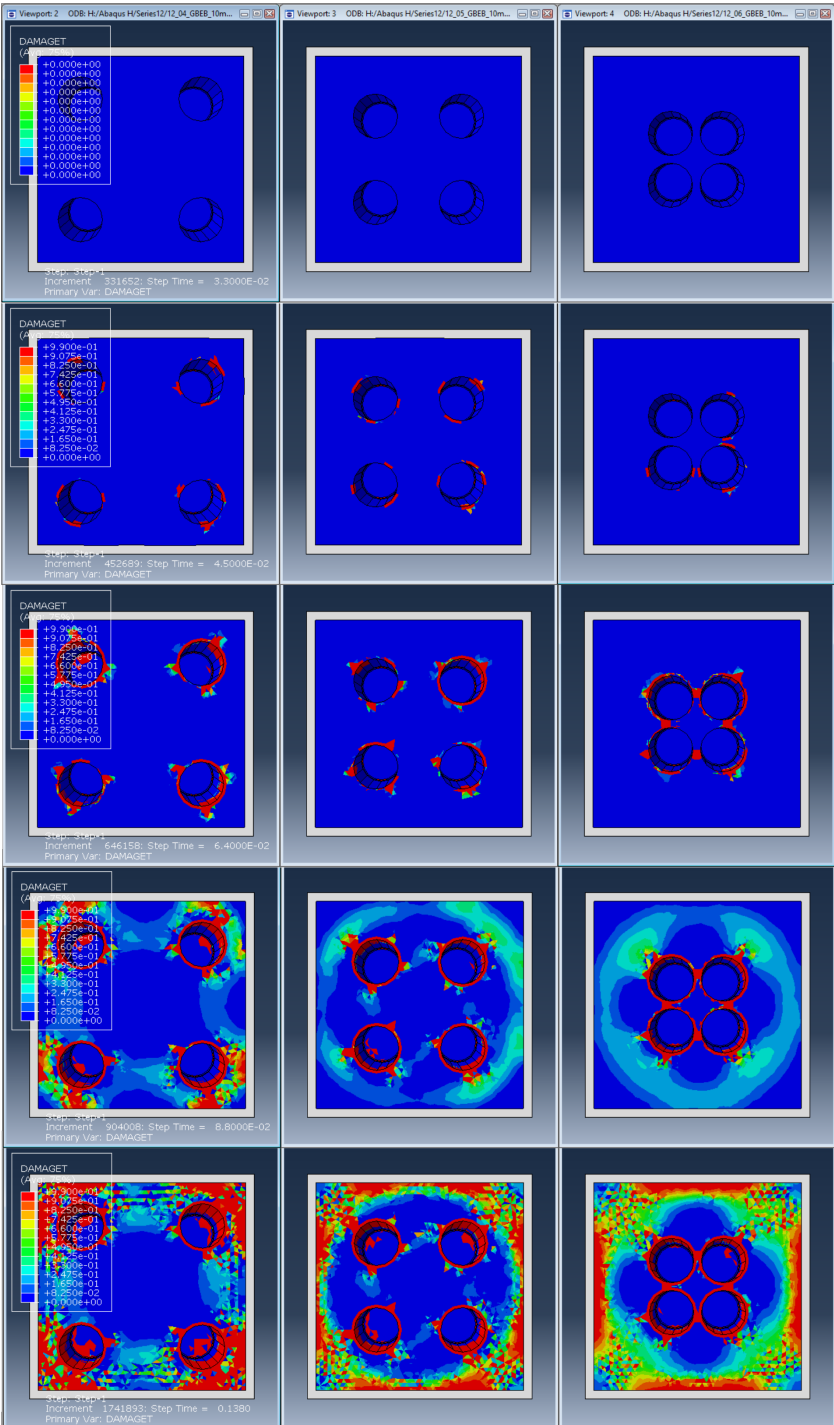


Figure E.1: DAMAGET of CGBEB type B4. B4C2 (left) B4C4 (middle) and B4C6 (right)

E.2. Comparison of stresses between B4C4 and a bottle in isolation

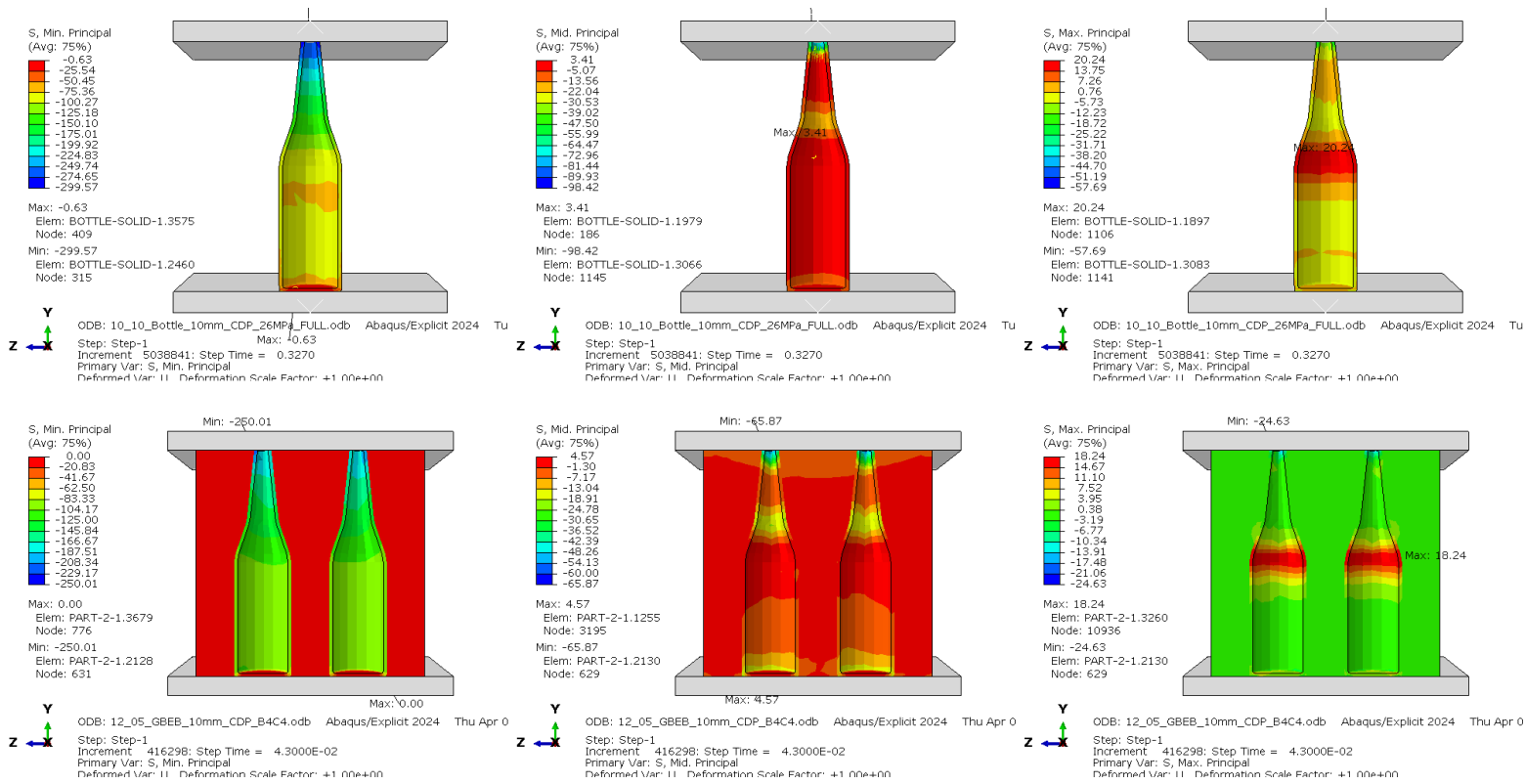


Figure E.3: S1, S2 and S3 before fracture of the glass

Interestingly, the maximum principal stress at the shoulder (before failure) is lower for the embedded bottle (18.24 MPa) than for the isolated one (20.24 MPa): embedded in the matrix, the bottle fails at a lower maximum principal stress. However, this does not indicate that the bottle is weaker. In the isolated case, it is loaded uniaxially, whereas the embedded bottle also carries compressive stresses imposed by the confining matrix. At the shoulder, the maximum principal stress, σ_1 , are oriented tangent to the surface, acting along the hoop direction. The meridional principal stress for embedded bottles is higher (4.57 MPa) than for isolated bottles (3.41 MPa). These stresses act in the direction of the bottle profile. This higher stress is due to the compressive stresses acting on the curve of the shoulder by the earthcrete. This higher meridional principal stress in combination with the slightly lower maximum principal stress is likely the reason why it fails at a lower σ_1 .

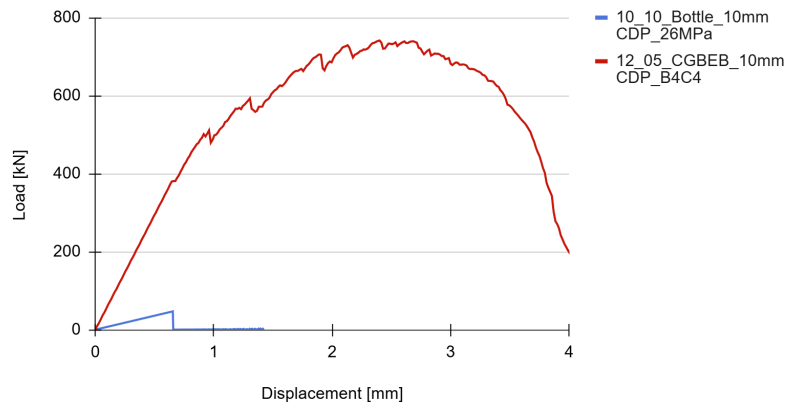


Figure E.4: Comparison isolated bottle with B4C4 block.

F

FEM simulations B6C2

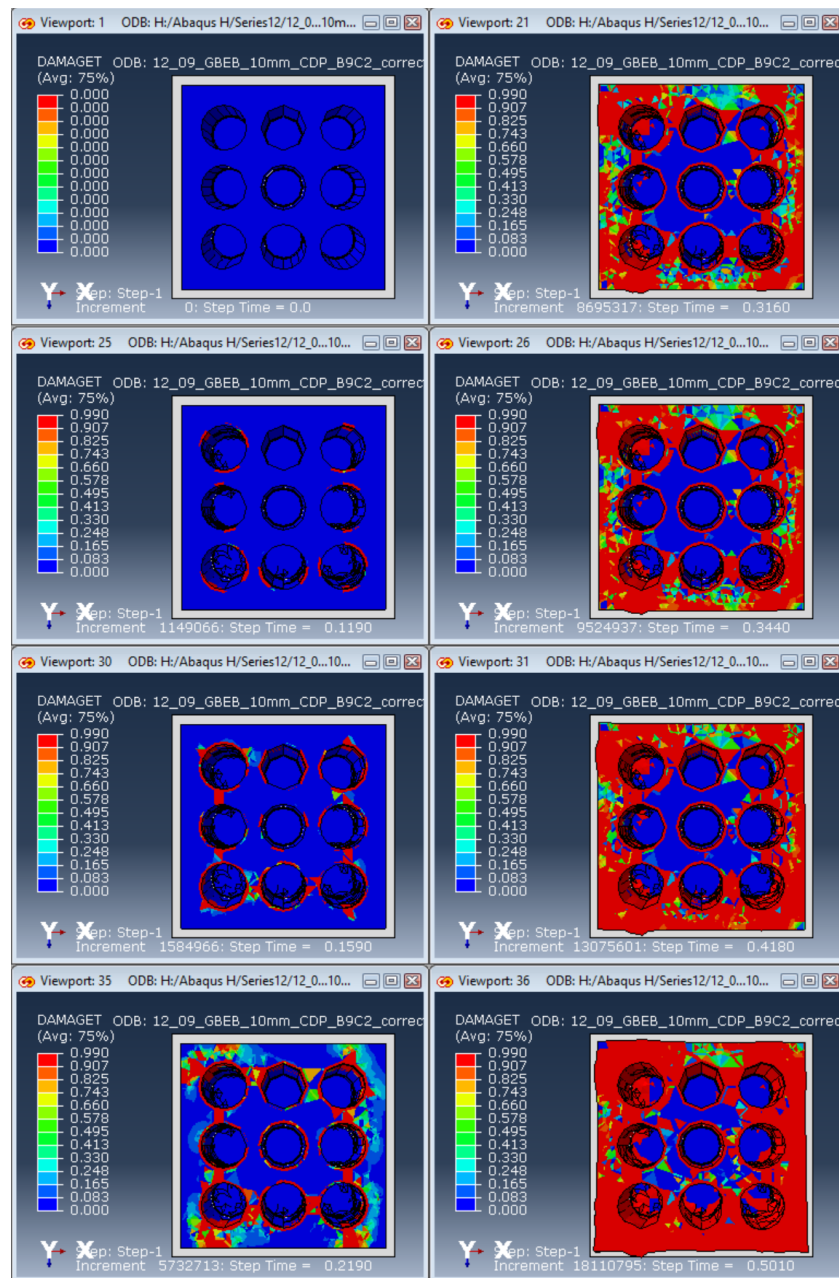


Figure F.1: Tensile damage of configuration B6C2

G

Visual inspection of the blocks

G.1. Surface imperfections



(a) Block top side (1)



(b) Block top side (2)



(c) Block edge chipping mold disassembly



(d) Block top side (3)



(e) Protruding top of the bottle



(f) Protruding top of the bottle



(g) Edge chipping

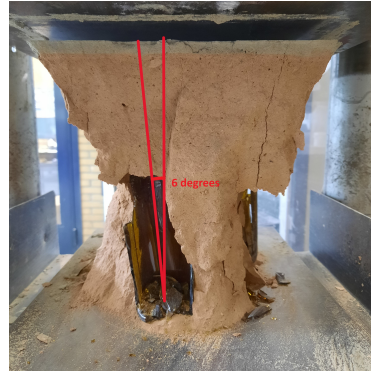
Figure G.1: Visual inspection of the blocks

G.2. Incline angle of the bottles within the block

Note that the incline angle shown below are rough estimates, measured from the figures, instead of direct measurements on site. The biggest incline angle measured 7 degrees in block #5.



(a) Incline angle (7°) of glass bottle in B4C4 #5.

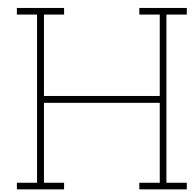


(b) Incline angle (6°) of glass bottle in B5C4 #10



(c) Incline angle (0°) of glass bottles in B5C4 #9

Figure G.2: Incline angle variations of glass bottles in the blocks



Cohesive zone modeling

The CZM simulation showed damage mostly in the neck and bottom part of the bottle. These are the regions where the bottle receives and transfers the load through the bearing surfaces. The capacity was also lower compared to the merged version. In the experiments, the neck region usually stayed intact which is better reflected in the merged variant. Thus the cohesive implementation was not refined further within the scope of this thesis. Both models have a glass strength of 3.7 MPa.

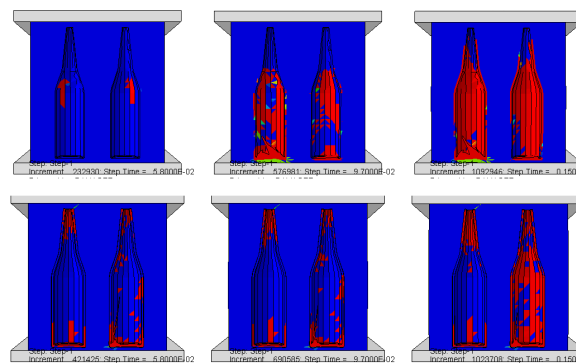


Figure H.1: Tensile damage at glass fracture in B4C4: merged interface (top) versus cohesive interface (bottom)

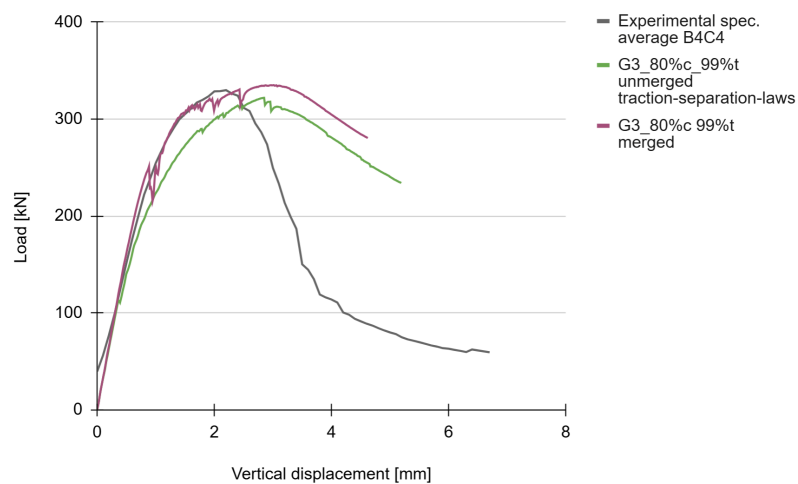


Figure H.2: Influence of CZM in B4C4

The input values for the CZM simulations are:

- **Normal behavior:** “hard” contact, preventing interpenetration of the surfaces.
- **Tangential behavior:** frictionless. After debonding, the surfaces transfer no shear; the bottle interacts with the matrix through normal (bearing) contact only.
- **Cohesive behavior:** default contact enforcement, i.e. the traction–separation stiffnesses are computed automatically by Abaqus.
- **Damage:** initiation by the maximum nominal stress criterion, with the bond strength of 0.96 N/mm^2 entered for the normal and 0.5 N/mm^2 for the shear directions, assumed in the absence of measured shear data (Section 7.7); evolution of type “energy” with a fracture energy of $1.1 \times 10^{-4} \text{ N/mm}$ (equal to the reported 0.11 J/m^2).

I

Alternating vertically oriented bottles B4C4

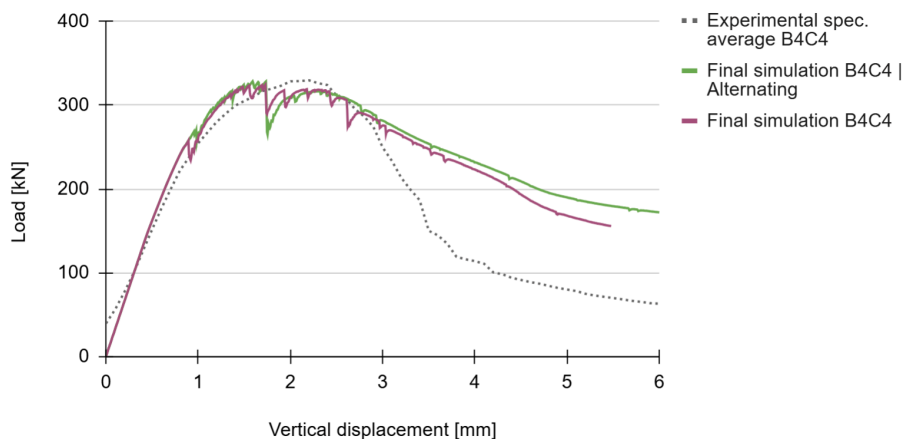


Figure I.1: Influence of alternating bottle orientation of B4C4

In the alternating variant of the B4C4 block, two of the four bottles are inverted by 180 degrees while the other two remain upright. This inversion creates an asymmetry in the block with the shoulders of adjacent bottles located at different heights. As a result, the damage that propagates from the shoulder to the matrix also becomes asymmetrical, with damage bands connecting the shoulder regions of neighboring bottles. Numerically, the loss of geometric symmetry also carries over to the mesh, which is less regular than in the symmetrical configuration.

The height difference between the shoulders also changes the F-u response: the post-peak behavior is more ductile than that of the symmetrical variant, as depicted in Figure I.1, and the first notable load

drop occurs later, at $t = 0.978$ s. Because the shoulder damage does not initiate in a single horizontal plane, the height difference spreads the fracture zone over a larger region, making the failure less brittle. The overall difference between the two configurations remains small, however, so the bottle orientation is of minor influence on the global response.

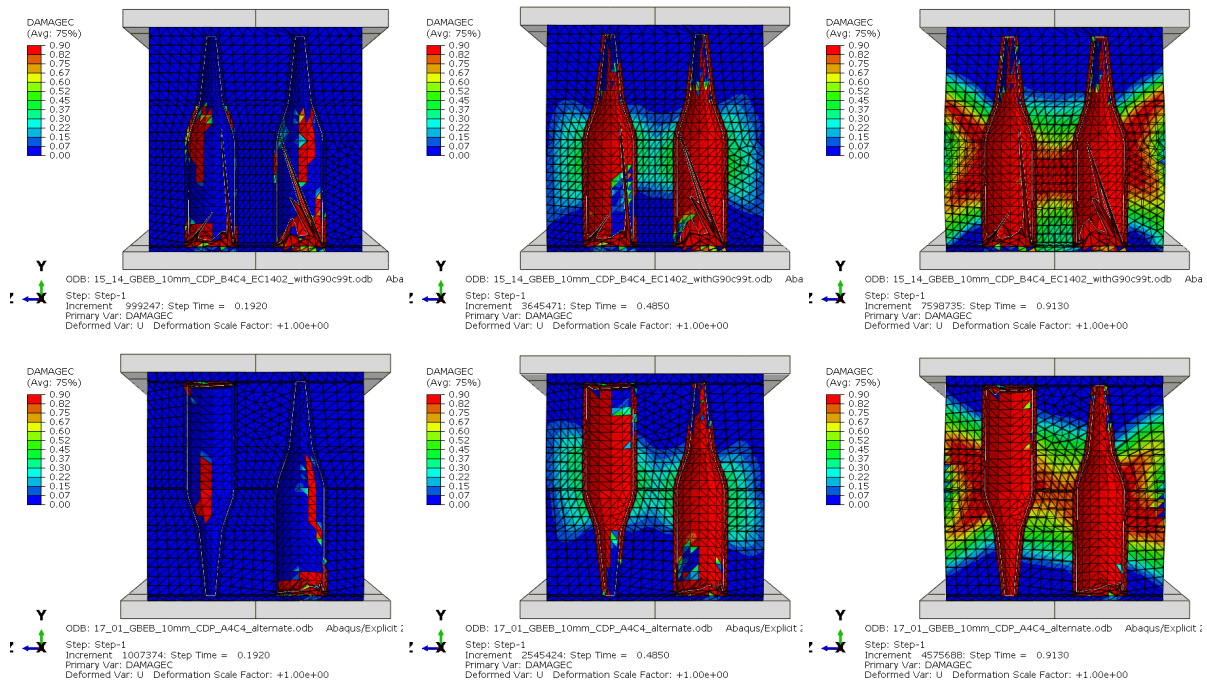


Figure I.2: Influence of alternating bottle orientation of B4C4

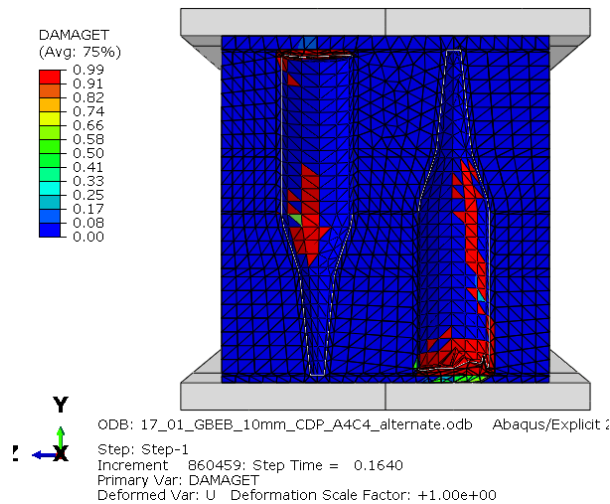


Figure I.3: Influence of alternating bottle orientation of B4C4 at $t = 0.978$ s.

J

Material properties tables

MATERIAL PROPERTIES CDP											
Chapter 6.3 Effect of changes to tensile & compression damage in glass with 10mm mesh Figure 6.10 and 6.11											
Explicit	Model	10_11_Bottle_10mm_CDP_26MPa				Submitted					
Density	2.50E-09	tonne/mm3				Terminated					
E_0	45500	N/mm2				Symmetry					
Poisson	0.23					Time step	0.001				
Dilitation angle	5										
Eccentricity	0.1										
fb0 / fc0	1.16										
K	0.67										
Viscosity param	0										
Sigma_tu	26	yield point									
Sigma_cu	800	crushing point									
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0		25	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001		0.25	0.00055	0.99	0.00055	0.00001
Explicit	Model	10_16_Bottle_10mm_CDP_26MPa									
Density	2.50E-09	tonne/mm3									
E_0	45500	N/mm2									
Poisson	0.23					Time step	0.001				
Dilitation angle	5										
Eccentricity	0.1										
fb0 / fc0	1.16										
K	0.67										
Viscosity param	0										
Sigma_tu	26	yield point									
Sigma_cu	800.00000	crushing point									
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	800.00000	0.00000	0.00000	0.00000	0.00000		25	0	0	0	0
	200.0000000	0.01320	0.75000	0.01320	0.00001		0.25	0.00055	0.99	0.00055	0.00001
Explicit	Model	10_17_Bottle_10mm_CDP_26MPa									
Density	2.50E-09	tonne/mm3									
E_0	45500	N/mm2									
Poisson	0.23					Time step	0.001				
Dilitation angle	5										
Eccentricity	0.1										
fb0 / fc0	1.16										
K	0.67										
Viscosity param	0										
Sigma_tu	26	yield point									
Sigma_cu	800	crushing point									
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0		25	0	0	0	0
	600	0.00441	0.25	0.00441	0.00001		0.25	0.00055	0.99	0.00055	0.00001
Explicit	Model	10_21_Bottle_10mm_CDP_26MPa									
Density	2.50E-09	tonne/mm3									
E_0	45500	N/mm2									
Poisson	0.23					Time step	0.001				
Dilitation angle	5										
Eccentricity	0.1										
fb0 / fc0	1.16										
K	0.67										
Viscosity param	0										
Sigma_tu	100	yield point									
Sigma_cu	45,500.00000	crushing point									
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	800.00000	0.00000	-29.76923	0.00000	309,600,000,000		25	0	0	0	0
	8.0000000	0.01742	0.69231	0.01742	-7,199,999,999.9		0.25	0.00055	0.99	0.00055	0.00001
Explicit	Model	10_22_Bottle_10mm_CDP_26MPa									
Density	2.50E-09	tonne/mm3									
E_0	45500	N/mm2									
Poisson	0.23					Time step	0.001				
Dilitation angle	5										
Eccentricity	0.1										
fb0 / fc0	1.16										

K	0.67													
Viscosity param	0													
Sigma_tu	25	yield point												
Sigma_cu	800	crushing point												
		inelastic strain	damage param	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP)	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0					25	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					18.75	0.00015	0.25	0.00015	0.00001
Explicit	Model	10_23_Bottle_10mm_CDP_26MPa												
Density	2.50E-09	tonne/mm3												
E_0	45500	N/mm2												
Poisson	0.23					Time step	0.001							
Dilatation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity param	0													
Sigma_tu	25	yield point												
Sigma_cu	800	crushing point												
		inelastic strain	damage param	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP)	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0					25	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					12.5	0.00028	0.5	0.00028	0.00001
Explicit	Model	10_24_Bottle_10mm_CDP_26MPa												
Density	2.50E-09	tonne/mm3												
E_0	45500	N/mm2												
Poisson	0.23					Time step	0.001							
Dilatation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity param	0													
Sigma_tu	25	yield point												
Sigma_cu	800	crushing point												
		inelastic strain	damage param	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP)	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0					25	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					6.25	0.00042	0.75	0.00042	0.00001
Explicit	Model	10_25_Bottle_10mm_CDP_26MPa												
Density	2.50E-09	tonne/mm3												
E_0	45500	N/mm2												
Poisson	0.23					Time step	0.001							
Dilatation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity param	0													
Sigma_tu	25	yield point												
Sigma_cu	800	crushing point												
		inelastic strain	damage param	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP)	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0					25	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					0.25	0.00055	0.99	0.00055	0.00001
Chapter 6.3 Effect of changes to tensile & compression damage in glass with 10mm mesh Figure 6.12														
Explicit	Model	10_05_Bottle_10mm_CDP_26MPa				Submitted								
Density	2.50E-09	tonne/mm3				Terminated								
E_0	45500	N/mm2				Symmetry	Yes							
Poisson	0.23					Time step	0.001							
Dilatation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity param	0													
Sigma_tu	26	yield point												
Sigma_cu	800	crushing point												
		inelastic strain	damage param	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP)	Cracking strain	Damage param	Cracking strain	e_pl
	800	0	0	0	0					26	0	0	0	0

		400	0.0088	0.5	0.0088	0.00001		0.26	0.00059	0.99	0.00059	0.00002	
Explicit	Model	10_11_Bottle_10mm_CDP_26MPa				Submitted							
Density	2.50E-09	tonne/mm3				Terminated							
E_0	45500	N/mm2				Symmetry							
Poisson	0.23					Time step	0.001						
Dilatation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point						GFI	0.003				
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
Explicit	Model	10_13_Bottle_10mm_CDP_26MPa				Submitted							
Density	2.50E-09	tonne/mm3				Terminated							
E_0	45500	N/mm2				Symmetry							
Poisson	0.23					Time step	0.001						
Dilatation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point						GFI	0.004				
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
Explicit	Model	10_14_Bottle_10mm_CDP_26MPa				Submitted							
Density	2.50E-09	tonne/mm3				Terminated							
E_0	45500	N/mm2				Symmetry							
Poisson	0.23					Time step	0.001						
Dilatation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point						GFI	0.002				
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
Explicit	Model	10_15_Bottle_10mm_CDP_26MPa				Submitted							
Density	2.50E-09	tonne/mm3				Terminated							
E_0	45500	N/mm2				Symmetry							
Poisson	0.23					Time step	0.001						
Dilatation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point						GFI	0.001				
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
Chapter 7.3 Influence of different glass properties on the response curve of the FEM model with Bottle B													
Explicit 6													
Density	2.50E-09	tonne/mm3											
E_0	45500	N/mm2											
Poisson	0.23												
Dilatation angle	5												
Eccentricity	0.1												

fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	37.5	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain								
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Concrete tensile behaviour		Concrete tension damage		
	800	0	0	0	0			Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	50	0.0165	0.9375	0.0165	0.00002			37.5	0	0	0	0
								0.375	0.00085	0.99	0.00085	0.00003
Explicit 11												
Density	2.50E-09	tonne/mm3										
E_0	45500	N/mm2										
Poisson	0.23											
Dililation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	100	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain								
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Concrete tensile behaviour		Concrete tension damage		
	800	0	0	0	0			Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	50	0.0165	0.9375	0.0165	0.00002			100	0	0	0	0
								1	0.003	0.99	0.003	0.00082
Explicit 12												
Density	2.50E-09	tonne/mm3										
E_0	45500	N/mm2										
Poisson	0.23											
Dililation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	70	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain								
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Concrete tensile behaviour		Concrete tension damage		
	800	0	0	0	0			Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	50	0.0165	0.9375	0.0165	0.00002			70	0	0	0	0
								0.7	0.0016	0.99	0.0016	0.00008
Explicit 14												
Density	2.50E-09	tonne/mm3										
E_0	45500	N/mm2										
Poisson	0.23											
Dililation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	37	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain								
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Concrete tensile behaviour		Concrete tension damage		
	800	0	0	0	0			Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl
	400	0.0088	0.5	0.0088	0.00001			37	0	0	0	0
								18.5	0.00045	0.5	0.00045	0.00004
Explicit 6												
Density	2.50E-09	tonne/mm3										
E_0	45500	N/mm2										
Poisson	0.23											
Dililation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	37.5	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain								
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Concrete tensile behaviour		Concrete tension damage		
								Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl

	800	0	0	0	0		37.5	0	0	0	0	
	50	0.0165	0.9375	0.0165	0.00002		0.375	0.00085	0.99	0.00085	0.00003	
Explicit 15												
Density	2.50E-09	tonne/mm3										
E_0	45500	N/mm2										
Poisson	0.23											
Dililation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	37	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	800	0.00000	0.00000	0.00000	0.00000		37	0	0	0.00000	0.00000	
	400	0.00880	0.50000	0.00880	0.00001		0.37	0.00084	0.99000	0.00084	0.00003	
7.4. Influence of the earthcrete material model on the FEM response curve												
Explicit 32												
Density	1.80E-09	tonne/mm3										
E_0	445	N/mm2										
Poisson	0.3											
Dililation angle	31											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	4	yield point										
Sigma_cu	5.064934298	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	4.4584	0	0	0	0		4	0	0	0	0	
	5.064934298	0.002	0	0.002	0.002		0.275	0.009	0.93125	0.009	0.00063	
	0.05	0.1	0.99013	0.1	0.08873							
Explicit 34												
Density	1.80E-09	tonne/mm3										
E_0	445	N/mm2										
Poisson	0.3											
Dililation angle	31											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	3	yield point										
Sigma_cu	5.064934298	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	4.4584	0	0	0	0		3	0	0	0	0	
	5.064934298	0.002	0	0.002	0.002		0.03	0.008	0.99	0.008	0.00133	
	0.05	0.1	0.99013	0.1	0.08873							
Explicit 37												
Density	1.80E-09	tonne/mm3										
E_0	445	N/mm2										
Poisson	0.3											
Dililation angle	31											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	2	yield point										
Sigma_cu	445	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	4.4584	0	0	0	0		2	0	0	0	0	
	5.064934298	0.002	0	0.002	0.002		0.02	0.000943396	0.7	0.000943396	0.000838527086	
	0.05	0.1	0.99989	0.1	-0.89989							
7.6. Sensitivity of the response to the earthcrete parameters												
Explicit	Model	08_01_GBEB_12mm_CDP_EC32_sym			Submitted	Wed Jan 21 12:01 2026						
Density	2.50E-09	tonne/mm3			Terminated	Thur Jan 22 11:40 2026						
E_0	45500	N/mm2			Symmetry	Yes						

[illegible]

Sigma_tu	37	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage parame	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage parame	Cracking strain	e_pl	
	800	0	0	0	0		37	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001		0.37	0.00084	0.99	0.00084	0.00003	
Explicit 32												
Density	1.80E-09	tonne/mm3										
E_0	445	N/mm2										
Poisson	0.3											
Dilittation angle	31											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity parame	0											
Sigma_tu	4	yield point										
Sigma_cu	5.034934298	crushing point										
		inelastic strain	damage parame	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage parame	Cracking strain	e_pl	
	4.6584	0	0	0	0		4	0	0	0	0	
	5.034934298	0.002	0	0.002	0.002		0.275	0.009	0.93125	0.009	0.00063	
	0.05	0.1	0.99007	0.1	0.0888		0.04	0.012	0.99	0.012	0.0031	
Explicit	Model	08_04_GBEB_12mm_CDP_EC32_sym			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry	Yes						
Poisson	0.23											
Dilittation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity parame	0											
Sigma_tu	37	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage parame	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage parame	Cracking strain	e_pl	
	800	0	0	0	0		37	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001		0.37	0.00084	0.99	0.00084	0.00003	
Explicit 32												
Density	1.80E-09	tonne/mm3										
E_0	445	N/mm2										
Poisson	0.3											
Dilittation angle	31											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity parame	0											
Sigma_tu	4	yield point										
Sigma_cu	5.034934298	crushing point										
		inelastic strain	damage parame	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage parame	Cracking strain	e_pl	
	4.6584	0	0	0	0		4	0	0	0	0	
	5.034934298	0.002	0	0.002	0.002		0.275	0.009	0.93125	0.009	0.00063	
	0.05	0.09	0.99007	0.09	0.0788		0.04	0.01	0.99	0.01	0.0011	
Explicit	Model	08_05_GBEB_12mm_CDP_EC32_sym			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry	Yes						
Poisson	0.23											
Dilittation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity parame	0											
Sigma_tu	37	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage parame	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage parame	Cracking strain	e_pl	
	800	0	0	0	0		37	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001		0.37	0.00084	0.99	0.00084	0.00003	

Explicit 32														
Density	1.80E-09	tonne/mm3												
E_0	445	N/mm2												
Poisson	0.3													
Dililtation angle	31													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity paramè	0													
Sigma_tu	4.2	yield point												
Sigma_cu	5.034934298	crushing point												
		inelastic strain	damage paramè	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP	Cracking strain	Damage paramè	Cracking strain	e_pl
	4.6584	0	0	0	0					4.2	0	0	0	0
	5.034934298	0.002		0	0.002	0.002				0.275	0.009	0.93452	0.009	0.00018
	0.05	0.1	0.99007	0.1	0.0888					0.042	0.01	0.99	0.01	0.00066
Explicit	Model	08_06_GBEB_12mm_CDP_EC32_sym			Submitted									
Density	2.50E-09	tonne/mm3			Terminated									
E_0	45500	N/mm2			Symmetry	Yes								
Poisson	0.23													
Dililtation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity paramè	0													
Sigma_tu	37	yield point												
Sigma_cu	800	crushing point												
	sigma_c [MPa]	inelastic strain	damage paramè	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
		e_c - in	d_c	e_c - in	e_pl					Yield stress (MP	Cracking strain	Damage paramè	Cracking strain	e_pl
	800	0	0	0	0					37	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					0.37	0.00084	0.99	0.00084	0.00003
Explicit 32														
Density	1.80E-09	tonne/mm3												
E_0	445	N/mm2												
Poisson	0.3													
Dililtation angle	31													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity paramè	0													
Sigma_tu	3.8	yield point												
Sigma_cu	5.034934298	crushing point												
		inelastic strain	damage paramè	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl					Yield stress (MP	Cracking strain	Damage paramè	Cracking strain	e_pl
	4.6584	0	0	0	0					3.8	0	0	0	0
	5.034934298	0.002		0	0.002	0.002				0.275	0.009	0.92763	0.009	0.00108
	0.05	0.1	0.99007	0.1	0.0888					0.038	0.01	0.99	0.01	0.00155
Explicit	Model	08_07_GBEB_12mm_CDP_EC32_sym			Submitted									
Density	2.50E-09	tonne/mm3			Terminated									
E_0	45500	N/mm2			Symmetry	Yes								
Poisson	0.23													
Dililtation angle	5													
Eccentricity	0.1													
fb0 / fc0	1.16													
K	0.67													
Viscosity paramè	0													
Sigma_tu	37	yield point												
Sigma_cu	800	crushing point												
	sigma_c [MPa]	inelastic strain	damage paramè	inelastic strain						Concrete tensile behaviour		Concrete tension damage		
		e_c - in	d_c	e_c - in	e_pl					Yield stress (MP	Cracking strain	Damage paramè	Cracking strain	e_pl
	800	0	0	0	0					37	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001					0.37	0.00084	0.99	0.00084	0.00003
Explicit 32														
Density	1.80E-09	tonne/mm3												
E_0	445	N/mm2												
Poisson	0.3													
Dililtation angle	31													
Eccentricity	0.1													

[illegible]

		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
e_c [%]	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	4.6584	0	0	0	0		4.1	0	0	0	0	
	5.064934298	0.002	0	0.002	0.002		0.41	0.009	0.9	0.009	0.00071	
	0.05	0.1	0.99013	0.1	0.08873		0.041	0.01	0.99	0.01	0.00088	
8.2. Material model calibration for mesh sensitivity												
Explicit	Model	10_01_Bottle_10mm_CDP_32MPa			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry	Yes						
Poisson	0.23				Time step	0.001						
Dilitation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	32	yield point										
Sigma_cu	800.00000	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	800.00000	0.00000	0.00000	0.00000	0.00000		32.00000	0.00000	0.00000	0.00000	0.00000	
	400.0000000	0.00880	0.50000	0.00880	0.00001		0.3200000	0.0008400	0.99000	0.00084	0.00014	
Explicit	Model	10_02_Bottle_10mm_CDP_30MPa			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry							
Poisson	0.23				Time step	0.001						
Dilitation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	100	yield point										
Sigma_cu	45,500.00000	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	800.00000	0.00000	-29.76923	0.00000	309,600,000,000		30.00000	0.00000	0.00000	0.00000	0.00000	
	400.0000000	0.00880	-14.38462	0.00880	149,600,000,000		0.3000000	0.0008400	#DIV/0!	0.00084	#DIV/0!	
Explicit	Model	10_03_Bottle_10mm_CDP_27MPa			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry							
Poisson	0.23				Time step	0.001						
Dilitation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	27	yield point										
Sigma_cu	800.00000	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	800.00000	0.00000	0.00000	0.00000	0.00000		27.00000	0.00000	0.00000	0.00000	0.00000	
	400.0000000	0.00880	0.50000	0.00880	0.00001		0.2700000	0.0008400	0.99000	0.00084	0.00025	
Explicit	Model	10_04_Bottle_10mm_CDP_27MPa			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry							
Poisson	0.23				Time step	0.001						
Dilitation angle	5											
Eccentricity	0.1											
fb0 / fc0	1.16											
K	0.67											
Viscosity param	0											
Sigma_tu	27	yield point										
Sigma_cu	800	crushing point										
		inelastic strain	damage param	inelastic strain			Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl		Yield stress (MP	Cracking strain	Damage param	Cracking strain	e_pl	
	800	0	0	0	0		27	0	0	0	0	
	400	0.0088	0.5	0.0088	0.00001		0.27	0.00061	0.99	0.00061	0.00002	
Explicit	Model	10_05_Bottle_10mm_CDP_26MPa			Submitted							
Density	2.50E-09	tonne/mm3			Terminated							
E_0	45500	N/mm2			Symmetry	Yes						

Poisson	0.23					Time step	0.001						
Dilatation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point											
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MP)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
8.3. Numerical results of the CGBEBs													
Explicit	Model	12_00_GBEB_10mm_CDP_B0C0 to 12_10_GBEB_10mm_CDP_B9IS0											
Density	2.50E-09	tonne/mm3											
E_0	45500	N/mm2											
Poisson	0.23					Time step	0.001						
Dilatation angle	5					Merged	yes						
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point											
Sigma_cu	800	crushing point											
	GLASS	inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MP)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	0
	400	0.0088	0.5	0.0088	0.00001			0.26	0.00059	0.99	0.00059	0.00002	
Explicit	This one fits the average of the vertical EB for article												
Mesh	10	mm											
Density	1.80E-09	tonne/mm3											
E_0	1200	N/mm2											
Poisson	0.3												
Dilatation angle	31												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
elastic_strain_c	0.006356968	7.8	crushing point										
elastic_strain_t	0.001629992	2	yield point										
	EC	inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			sigma_t [MPa]	e_t - in	d_t	e_t - in	e_pl	
	5.8	0	0	0				8.28	0	0	0	0	0
	8	0.0034	0.0034	0.0034				0.0828	0.0071	0.99	0.0071	0.014669927	
	7	0.0074	0.0074	0.00657									
	5	0.0124	0.0124	0.0099									
	2	0.0204	0.0204	0.0154									
	0.6	0.0284	0.0284	0.0284									
8.6. Effect of merged versus unmerged geometry													
Explicit	Model	13_01_GBEB_10mm_CDP_B4C4_updatedMP				Submitted							
Density	2.50E-09	tonne/mm3				Terminated							
E_0	42000	N/mm2				Symmetry							
Poisson	0.23					Time step	0.001						
Dilatation angle	5					Merged	no						
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity parameter	0												
Sigma_tu	26	yield point											
Sigma_cu	800	crushing point											
		inelastic strain	damage parameter	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			Yield stress (MP)	Cracking strain	Damage parameter	Cracking strain	e_pl	
	800	0	0	0	0			26	0	0	0	0	0
	8	0.01905	0.99	0.01905	0.00019			0.26	0.000619	0.99	0.00062	0.00001	
Explicit	This one fits the average of the vertical EB for article												
Mesh	10	mm											
Density	1.80E-09	tonne/mm3											
E_0	E_0	N/mm2											
Poisson	0.3												
Dilatation angle	31												
Eccentricity	0.1												

[illegible]

[illegible]

[illegible]

3.839315241	0.001081323185	0	0.001081323185						
3.980098801	0.001393964121	0	0.001393964121						
4.097743799	0.001727784695	0	0.001727784695						
4.197454437	0.002068868485	0	0.002068868485						
4.310264077	0.002403454563	0	0.002403454563						
4.3860996	0.002764594032	0	0.002764594032						
4.435402003	0.003147641755	0	0.003147641755						
4.511485915	0.003506006565	0	0.003506006565						
4.565258843	0.003885370143	0	0.003885370143						
4.605943921	0.004270705602	0	0.004270705602						
4.663144427	0.004646449844	0	0.004646449844						
4.689797225	0.005044728381	0	0.005044728381						
4.732061997	0.005432014335	0	0.005432014335						
4.75966575	0.005828149223	0	0.005828149223						
4.78999881	0.006222817095	0	0.006222817095						
4.784037882	0.006641947175	0	0.006641947175						
4.808367083	0.007041940975	0	0.007041940975						
4.835688603	0.007438554337	0	0.007438554337						
4.844243746	0.007848874394	0	0.007848874394						
4.85012977	0.008261621785	0	0.008261621785						
4.859952025	0.008668997091	0	0.008668997091						
4.861514538	0.009085198645	0	0.009085198645						
4.879548254	0.009490553695	0	0.009490553695						
4.876535074	0.009910243082	0	0.009910243082						
4.862592945	0.01033423508	0	0.01033423508						
4.855651154	0.01075665976	0.001206081905	0.01075665976						
4.828795332	0.01119527076	0.006730249702	0.01119527076						
4.671115802	0.01172322945	0.03916448971	0.01172322945						
4.639216944	0.01216654783	0.04572599592	0.01216654783						
4.619340965	0.01259613248	0.04981442961	0.01259613248						
4.561443679	0.01305314364	0.06172374	0.01305314364						
4.383451307	0.01360057079	0.09833627525	0.01360057079						
4.338002667	0.01405041728	0.1076849339	0.01405041728						
4.247476479	0.01453343375	0.1263059185	0.01453343375						
4.155265096	0.01501750051	0.1452735431	0.01501750051						
3.984615803	0.01555747737	0.1803756275	0.01555747737						
3.815925255	0.01609864532	0.2150748033	0.01609864532						
3.673166431	0.01661839407	0.2444398957	0.01661839407						
3.596887796	0.01708988046	0.2601301986	0.01708988046						
3.536482697	0.01755271815	0.2725553592	0.01755271815						
3.474130589	0.01801517911	0.2853810143	0.01801517911						
3.42454601	0.01846682856	0.2955804241	0.01846682856						
3.373726198	0.01891977872	0.3060339178	0.01891977872						
3.306756943	0.01938644937	0.319809307	0.01938644937						
3.275220618	0.019824436	0.3262962412	0.019824436						
3.183110201	0.02031040839	0.3452430975	0.02031040839						
3.096650029	0.02120330095	0.3630277141	0.02120330095						
3.049113549	0.02165884308	0.3728058356	0.02165884308						
2.984955313	0.02211842367	0.3860030061	0.02211842367						
2.903040207	0.02259674966	0.4028527152	0.02259674966						
2.871649746	0.02303444046	0.4093096456	0.02303444046						
2.817629239	0.02349258325	0.4204215134	0.02349258325						
2.779902076	0.02393630074	0.4281818856	0.02393630074						
2.751847502	0.02437447441	0.4339526334	0.02437447441						
2.725904678	0.02481001211	0.4392890001	0.02481001211						
2.701111723	0.02524177482	0.4443888418	0.02524177482						
2.622783993	0.02571476718	0.4605006377	0.02571476718						
2.590584419	0.02615489728	0.4671240005	0.02615489728						
2.556759987	0.02659766708	0.4740815919	0.02659766708						
2.527383438	0.02703533276	0.4801242661	0.02703533276						
2.489958185	0.02747965639	0.4878225365	0.02747965639						
2.464372547	0.02791422249	0.493085431	0.02791422249						
2.440238579	0.02834893545	0.498049721	0.02834893545						
2.411984383	0.02878828368	0.5038615304	0.02878828368						
2.383364764	0.02922603139	0.5097485063	0.02922603139						
2.360996495	0.02965689584	0.514349597	0.02965689584						
2.336507766	0.03009240468	0.5193868602	0.03009240468						
2.297866081	0.03053817679	0.5273353473	0.03053817679						
2.272896081	0.03097272991	0.5324716068	0.03097272991						
2.238303822	0.0314124381	0.539587138	0.0314124381						
2.207812001	0.03185431294	0.5458592207	0.03185431294						
2.139192736	0.03231717076	0.5599740123	0.03231717076						
2.062501216	0.03279292141	0.5757492444	0.03279292141						
2.009494624	0.03324788823	0.5866525528	0.03324788823						
1.97194674	0.03369186681	0.594376048	0.03369186681						
1.921666979	0.03414252259	0.6047184547	0.03414252259						
1.881267634	0.03458991861	0.6130284876	0.03458991861						
1.835942965	0.03503849252	0.6223516456	0.03503849252						
1.770706648	0.03550298539	0.6357705744	0.03550298539						
1.724138394	0.03595551296	0.6453495345	0.03595551296						
1.63633496	0.03643413802	0.6634104563	0.03643413802						

1.616803593	0.0368652748	0.6674280041	0.0368652748										
1.582761274	0.03730725433	0.6744304143	0.03730725433										
1.531885353	0.03776145161	0.6848954495	0.03776145161										
1.481852604	0.03821293582	0.6951870467	0.03821293582										
1.434622049	0.03866348535	0.7049022404	0.03866348535										
1.409454861	0.03910259459	0.7100790608	0.03910259459										
0.243055556	0.04869797483	0.9500041492	0.04869797483										
9.4.2 Numerical calibration of B4C4													
Explicit 1	This one fits the average of the vertical bottle for article												
Mesh	10												
Density	2.50E-09												
E_0	42000												
Poisson	0.23												
Dililation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity param	0												
		inelastic strain	damage param	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			sigma_t [MPa]	e_t - in	d_t	e_t - in		
0.00%	800	0	0	0	0			0.00%	26	0	0	0	
99.00%	8	0.019047619	0.99	0.019047619	0.000190476			99.00%	0.26	0.000619048	0.99	0.000619048	
This one fits the average of the vertical GBEB for article (stress corrosion)													
Mesh	10												
Density	2.50E-09												
E_0	6000												
Poisson	0.23												
Dililation angle	5												
Eccentricity	0.1												
fb0 / fc0	1.16												
K	0.67												
Viscosity param	0												
		inelastic strain	damage param	inelastic strain				Concrete tensile behaviour		Concrete tension damage			
	sigma_c [MPa]	e_c - in	d_c	e_c - in	e_pl			sigma_t [MPa]	e_t - in	d_t	e_t - in	e_pl	
0.00%	800	0	0	0	0			0.00%	3.714285714	0	0	0	0
90.00%	80	0.121333333	0.9	0.121333333	0.001333333			99.00%	0.037142857	0.000619048	0.99	0.000619048	0.00000619