

Modelling of Masonry Walls under Blast Loading: A Case Study of Nigerian Sandcrete

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ABSTRACT

Terror bombings have become a major problem in Nigeria over the past decade. In this study, the most widely used masonry unit in the country – sandcrete – is modelled as infill in a reinforced concrete frame under different scenarios of blast loading on the finite element software, Abaqus CAE. Through many variations, sandcrete is found to fail under low stresses as expected. Retrofitting with carbon fibre proves to be a very effective remediation measure – much more than internally reinforcing sandcrete with steel bars. Recognising that applying structural mitigation measures such as these two is not always possible, safe standoff distances were found in each case based on stress and displacement failure criteria. These distances can help designers to determine the locations of traffic barriers and other critical infrastructure when considering blast loading. These are seen as tangible measures that can be taken to protect lives and property.

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INTRODUCTION

With the rise in global terrorism over the past decade and a half, the structural integrity of civil engineering structures has become an increasing source of concern. This is understandable, as the potential for a major loss of life is considerable when civil engineering structures fail or are made to fail as in this case. Losses of life due to impact loading

on buildings from explosives have become a recurrent theme in global news. Among the countries worst hit by this new wave of terrorism is Nigeria. The devastating impacts of explosives on buildings and public places have left hundreds dead in the country since 2009. An example of such attack can be seen on Figure 1.1.



Figure 1.1: Bombed UN building in Abuja, Nigeria (CNN, 2011)

Most residential and office buildings in Nigeria are reinforced concrete frames with some form of masonry infill as walls. Sandcrete blocks have been reported to account for as much as 90% of all masonry used in Nigeria (Anosike and Oyebade, 2011). Due to economics, local expertise and other factors, it is not deemed that this is going to change soon.

Considerable work has been done on modelling masonry under blast loading as by Eamon (2007), Davidson et al (2004), and Mayrhofer (2001). However, these studies have tended to be generic and no study was found that relates directly to the aforementioned sandcrete buildings in Nigeria. This is even as researchers in Nigeria have been investigating such cases as shear walls subjected to blast loading (Ajimithuo et al., 2018). A study that involves modelling of sandcrete infills in reinforced concrete frames subjected to blast loading could potentially save lives in the future

in Nigeria and beyond, as sandcrete is also used in countries such as Ghana. Another similar cause of failure in buildings generally is a gas explosion. Modelling under explosive loading from bombs could obtain findings relevant to gas explosions.

LITERATURE REVIEW

Sandcrete and its Properties

The most widespread form of masonry infill in Nigeria is sandcrete. There is not a broad agreement in literature as to the exact definition of sandcrete. In Nigeria, it is a broad term encompassing all masonry units made up of cement, sand and water (Anosike and Oyebade, 2011). Sandcrete is made usually as hollow blocks but is sometimes also filled with concrete to become solid. Sandcrete has been in wide use in West Africa for over 6 decades (Oyetola and Abdullahi, 2006).



Figure 2.1: Typical sandcrete units in Nigeria (Crist, 2013)

As with most masonry, sandcrete is made up of units and mortar. Typically, sandcrete sizes are based on specifications found in the British Standards publications BS 2028 and BS 1364. The most widely-used size is 450mm x 225mm available in various thicknesses ranging from 63mm to 225mm (Yusuf and Hamza, 2011).

The compressive strength of masonry in the direction normal to the bed joints is traditionally regarded as its only relevant

structural material property (Lourenco, 1996). The Nigerian Industrial Standard (NIS) specifies this minimum compressive strength as 1.8 MPa at 7 days and 2.5 MPa at 28 days (Yusuf and Hamza, 2011). However, due to quality control problems, 28-day strengths of as low as 0.3 MPa have been recorded (Mohammed and Anwar, 2014). The elastic modulus of masonry can be found from the compressive strength using equation 2.1 below (British Standards Institution, 2005).



$$E = k_E f_k \quad \text{Eq. 2.1}$$

Where:

E is elastic modulus

k_E is a constant usually taken as 1000

f_k is the compressive strength of a masonry unit

The tensile strength of masonry is about 5-10% of its compressive strength (Spence and Kulthermann, 2016). Given that the compressive strength of masonry is itself low, the tensile strength is negligible and so is not considered in the design of sandcrete. The Poisson's ratio of sandcrete has not been much discussed in literature. However, sandcrete is a concrete-based material and such materials have a Poisson's ratio of the range 0.1-0.2. A modified regression method which was used by Onwuka et al to derive the ratios of soilcrete, a similar material (2021). They also got results in the region of 0.1-0.2. The density of sandcrete is around 2100 kg/m³ (Olufisayo, 2013).

Finite Element Modelling of Masonry

There are various methods of modelling masonry under blast loading. They are generally classified into three: experimental, analytical and numerical methods (Hao, 2015). The finite element method is a numerical method and is one of the most powerful tools of analysis and modelling in modern engineering. It is especially useful given its greater power and accuracy compared to analytical methods and its cost-savings compared to experimental methods. The central feature of the method is systematically partitioning a given domain or structure into an assembly of discrete subdomains called elements (Zohdi, 2014). The material properties of each part of the structure are assumed by the elements that replace it. Boundary conditions (fixed, pinned etc.) are assigned to each element depending on the situation. Approximate solutions for these elements are then determined individually before being coupled together to give a global solution valid over the whole domain. The accuracy of the global solution depends on the sizes and nature of the elements. The finer the mesh size (i.e. the smaller the elements), the more the solution obtained approaches the real solution (Darji and Vakaria, 2012).

Masonry is a composite material made up of brick/block units and mortar joints. As infill, this composite nature is expanded to include reinforced concrete. This fundamental composite behaviour of masonry is the starting point for understanding the methods of modelling masonry (Hao, 2015). There are two main methods of modelling masonry found in current literature: Heterogeneous/Micro-modelling and Homogeneous/Macro-modelling.

Micro-modelling is a detailed representation of units, mortar and the unit/mortar interface (Lourenco, 1996), and is the more accurate approach, but it is time consuming and requires and is computationally inefficient (Wang et al., 2009). Moreover, some of the minute details it considers only have a minor effect on modelling accuracy. For example, Lourenco has asserted that knowledge of the interaction between units and mortar is generally negligible for modelling global structural behaviour (1996).

In macro-modelling, the heterogeneous masonry material of brick and mortar matrix is modelled as one (Wei and Hao, 2006). A single set of material properties is given to masonry in this homogeneous model. Therefore it is of the utmost importance that values reflecting the real response of the structure are selected. Various methods have been developed to derive homogenised material properties of masonry. Ma et al., for example derived values for elastic modulus and strength using numerical simulations (2001).

Hao notes that most numerical studies, as well as the homogenised masonry material models are based on the static material properties of masonry (2015). These studies have not taken into account that masonry (like all structures) behaves differently under short term loading such as blast loading. Structures are typically stronger in short-term loading, so not considering this fact results in overestimating masonry strength.

Modelling Blast Loading

An explosion is an event, which results in a sudden release of energy that causes a rapidly moving blast or shock wave with a blast magnitude large enough to be potentially hazardous. The energy that is released suddenly is dissipated through various

mechanisms, including a pressure wave, debris and thermal radiation. Damage from an explosive is caused by this dissipation of energy (Crowl, 2003). When the explosive material decomposes at a rate that is above the speed of sound, it is called a detonation. Detonation produces high intensity shockwaves with velocities ranging from 1500-9000 m/s. Acts of terrorism usually involve detonation, and so are the subject of this study (Cormie et al., 2009).

A detonation reaction generates hot gases, which are at pressures 10-30 GPa and

temperatures of about 3000-4000°C. These hot gases expand violently, forcing the surrounding air out of the volume it occupies. This makes a layer of air surrounding the gaseous products highly compressed. This compressed layer is known as the blast wave and contains as pressure energy most of the energy released by the explosion (Cormie et al., 2009). The maximum value a pressure wave reaches is called the peak side-on overpressure or simply peak overpressure (P_{so}). Figure 2.2 shows variation of P_{so} with time in free air.

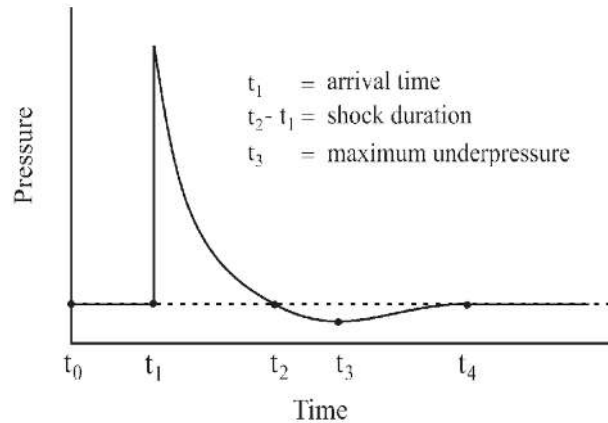


Figure 2.2: Typical pressure variation with time (Crowl, 2003).

Arrival time, t_1 is the time it takes for the pressure wave to reach the surface of the structure it is acting upon. The value of pressure here is P_{so} , as pressure is at its maximum. The pressure very quickly reduces to its ambient value at t_2 , crosses the neutral axis until it reaches a minimum negative value at t_3 and then returns to ambient at t_4 . The shock duration t_1-t_2 is important because it is usually the period of greatest destruction to structures and so is the most critical for predicting damage (Crowl, 2003). The same author further expounds that the period beyond t_2 is normally only critical in

very large explosions such as nuclear explosions. The explosions concerning this study are not powerful enough to warrant considering such.

Energy is dissipated as a blast wave travels further from the origin of the explosion. However, the volume of space affected by the blast increases as the cube of the distance from the blast. Energy and volume of space affected by a blast have an inverse cube relationship. A graphical representation of this relationship is reproduced in Figure 2.3.

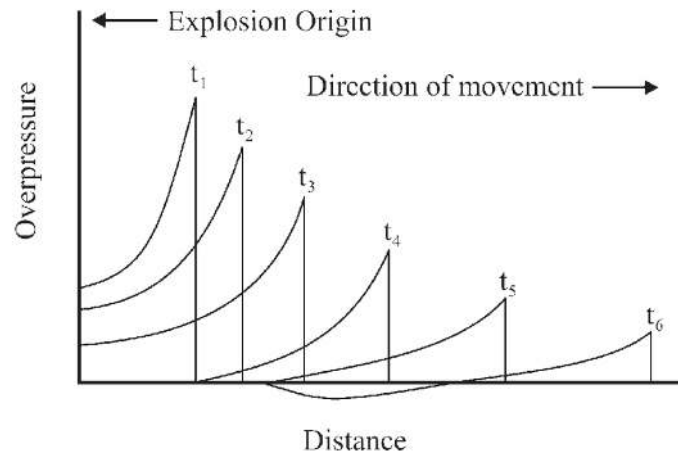


Figure 2.3: Overpressure curves at various times after initial explosion (Crowl, 2003)

Lastly, an explosion lasts for a very short time, typically around 0.01 seconds (Chock, 1999).

Improvised Explosive Devices (IEDs)

Terrorist organisations usually do not have access to conventional explosives, so they make use of devices called Improvised Explosive Devices (IEDs) (Cormie et al., 2009). The term IED came into popular usage during America's Iraq war from 2003 to date. IED's are defined simply as homemade bombs. Sophistication level of IED's ranges widely from small pipe bombs, to suicide vests, to those large enough to fit into a truck as in the

Oklahoma City Bombing in 1995 (U.S. Department of Homeland Security, 2009).

The magnitude of IEDs and other types of explosives are not measured directly. They are usually measured as equivalent masses of Trinitrotoluene (TNT). TNT explosions are well understood, so this makes calculations easier (Cormie et al., 2009). A procedure for calculating TNT equivalent in various cases can be found in (Crowl, 2003). Transport Canada has provided a table showing equivalent values of TNT for various explosives. This is reproduced as Table 2.1. The U.S. Department of Homeland Security has produced a similar table (2009).

Table 2.1: TNT equivalents for various IEDs (Transport Canada, 2012)

	Threat Description	Explosives Mass (TNT equivalent) ±
High Explosives (TNT Equivalent)	Pipe Bomb	2.3 kg
	Suicide Belt	4.5 kg
	Suicide Vest	9 kg
	Briefcase/Suitcase Bomb	23 kg
	Compact Sedan	227 kg
	Sedan	454 kg
	Passenger/Cargo Van	1 814 kg
	Small Moving Van/Delivery Truck	4 536 kg
	Moving Van/Water Truck	13 608 kg
	Semitrailer	27 216 kg



Calculation of Blast Pressure:

An explosion is defined by two important parameters; mass (W) and standoff distance, R (Ngo et al., 2007). Mass has already been explained as an equivalent of TNT. The strength of a blast wave decreases with distance. Therefore there is a distance beyond which people and even structures could be considered safe. The effects of reflection, however, often complicate this. In urban areas, surrounding buildings confine the blast wave, preventing it from freely expanding. This causes the channelling of blast waves along city streets, amplifying them. For this reason, blast waves could cause damage at what might otherwise be considered safe distances (Cormie et al, 2003).

Ngo et al., documents various different equations that have been worked out over the years for predicting blast pressure loads on structures (2007). Of them are Brode in 1955, Newmark and Hansen 1961 and more recently Mills in 1987. Brode's equations are more widely accepted. Cormie et al. for example only considered Brode's equations in their work (2009). All the different works above make use of a scaled distance parameter, Z in calculating peak overburden pressure.

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad \text{Eq. 2.2}$$

Where:

R = Distance from explosion centre

W = Equivalent mass of TNT

For Brode, the peak overburden pressure is in turn:

$$P_{so} = \frac{6.7}{Z^3} + 1 \text{ bar} \quad (P_{so} > 10 \text{ bar}) \quad \text{Eq. 2.3}$$

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{ bar} \quad (0.1 \text{ bar} < P_{so} < 10 \text{ bar}) \quad \text{Eq. 2.4}$$

P_{so} = Peak Overburden Pressure

1 bar = 100,000 Pa

Equation 2.3 applies to near field explosions, while equation 2.4 applies to far

field explosions. The pressures calculated from these equations will be modelled as the blast loads in this study.

There are other important factors in modeling blast loading such as the effects of ground shock (Wu and Hao, 2005). However Crowl has pointed out "it is generally recognized that simplistic damage estimates based on...overpressure only are adequate for structural damage predictions" (2003). A pressure only model is therefore justified.

Failure Criteria for Masonry

As with limit state design, two important distinct failure criteria can be specified for a masonry wall: one for displacements (serviceability), the other for stresses (ultimate). The first is typically more critical as Cormie et al. have noted that the controlling criterion in the design of blast-resisting structural elements is usually a limit of the deflection of the element (2009). In this vein, the US Army Corps of Engineers (USACE) has recommended "that the extreme deflection of an infill wall is close to its thickness, which can be used as a simple criterion to assess the collapse state of an unreinforced masonry wall under blast load" (Hao, 2015). In their experiments, Zapata and Weggel found collapse deflection of masonry to be close to the thickness of the masonry (2008). The failure criterion above though is too liberal and in practice is used to assess complete failure. According to the British Standards publication BS 5628-2, the total deflection of masonry should not exceed length/125 for cantilevers and span/250 for all other elements (2005).

The stress failure criterion is a direct comparison between applied stresses and the known breaking stress of NIS-approved sandcrete, which is 2.5 MPa. This criterion though is highly subjective as masonry properties are variable depending on mix design and quality control. This criterion is not rigorous and in practice, safety factors are applied when the stress criterion is considered. It remains a good benchmark guide however and is the easiest check on finite element software such as Abaqus.

MITIGATION MEASURES FOR MASONRY

When a structural element is dynamically loaded, the element deflects

continuously until the strain energy of the element is sufficiently developed to balance the energy produced by the blast load. The element either comes to rest, or breaks up into fragments. The primary objective in design of structures subjected to blast loading is to ensure the structure has sufficient ductility, so that it deflects only and does not break up into pieces (Crowl, 2003). Under blast loads, masonry is a weak and brittle material, which is likely to fail suddenly, breaking up into fragments and causing severe damage (Urgessa and Maji,

2006). Some of the most important methods of enhancing masonry strength under blast loads will be discussed in this section.

Internal Reinforcement of Masonry with Steel Bars

Here, masonry is internally reinforced with a stronger material to increase its ductility and strength. Steel bars are the primary materials used. Voids in masonry blocks are grouted to ensure steel and masonry become a composite whole. Figure 2.4 illustrates this.

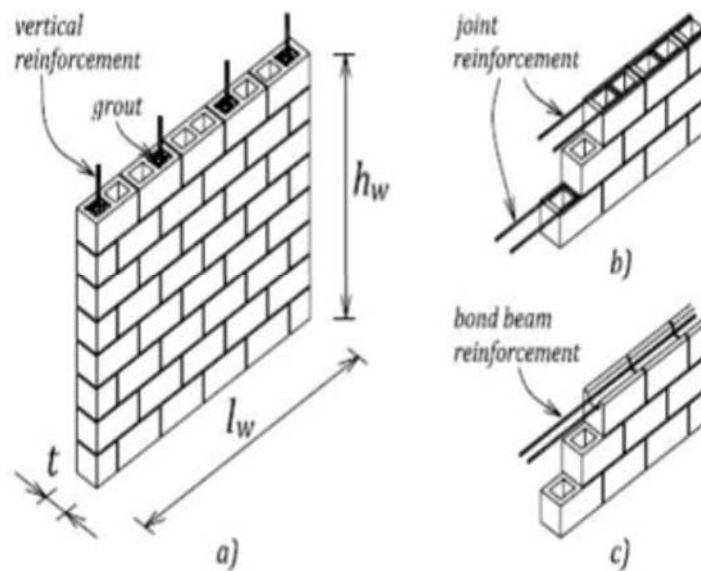


Figure 2.4: Steel bar reinforcement of masonry (Gem Nexus, 2013).

The primary disadvantage of this method is that it cannot be applied to existing structures as there is mortar between every level of blocks stacked. Clearly, methods that can be applied on existing structures are more useful than internal reinforcement methods. These "retrofitting" methods are discussed next.

Retrofitting Techniques

These are techniques used on already existing masonry structures. Different methods of retrofitting masonry have been developed over the years. They include using fibre-reinforced polymers (FRP), bonding of steel plates to surface, filling cracks and voids by grouting, jacketing by cast-in-situ concrete etc. Although cost-effective and efficient for

strength, bonding steel plates is problematic in that steel plates can be difficult to handle on site and increase dead loads on a structure (Ede, 2011). Grouting is problematic in that it can be difficult to determine locations of voids. Jacketing on the other hand restricts space in a structure and is not convenient from a constructability perspective.

Fibre reinforced polymers are lightweight and high strength fabrics (carbon, aramid, glass etc.) in an epoxy matrix that are bonded to the face of a structure. Under blast loads, these polymer composites enhance the out-of-plane bending strength of a wall and prevent fragments of the wall from entering the protected space in a building and harming people (Hamoush et al., 2001). Figure 2.5

shows an application of carbon fibre strips on masonry.



Figure 2.5: Unidirectional carbon fibre strips on masonry (Houlette, 2011).

Traffic Barriers and Standoff Distance

Traffic barriers are often used in high-risk areas to restrict access for vehicles, which could be laden with explosives. Blast loading is modelled as a pressure, which reduces as standoff distance increases. It follows that there

is a distance at which an explosive will no longer have devastating consequences. Traffic barriers are put in place with this safe distance in mind as can be seen on Figure 2.6 (Woolaston and Prigg, 2014).



Figure 2.6: A vehicle barrier stopping a truck

METHODOLOGY

Abaqus will be used to model a single 15m x 3m rectangular frame of concrete with masonry infill under blast loading. Concrete

columns and beams are all 450mm sided squares. The reinforcements specified are four 40mm bars arranged in a square pattern for both columns and beams. Links are 10mm at



400mm spaces. Cover is 75mm. All this conforms to Eurocode 2. Reinforcement has been modelled as an “embedded” material in concrete on Abaqus.

Masonry is modelled as one homogeneous block with a thickness of 225mm, which is the most common thicknesses of

sandcrete walls in Nigeria. The interface between masonry and concrete is defined simultaneously as Tangential, Rough and Normal, Hard on Abaqus. Explosion time is 0.01 seconds in each case. Table 3.1 below shows the material properties used in modelling.

Table 3.1: Material properties used in study

Material	Masonry	Concrete	Steel	Carbon Fibre
Density	2000 kg/m ³	2400 kg/m ³	8050 kg/m ³	1600 kg/m ³
Young's Modulus	2.5 x 10 ⁹ N/m ²	17 x 10 ⁹ N/m ²	200 x 10 ⁹ N/m ²	70 x 10 ⁹ N/m ²
Poisson's Ratio	0.15	0.15	0.3	0.1

The following parameters will be varied in the model. Where they are not being varied, default conditions and values will be used:

1. **Loading:** 3 scenarios will be considered using TNT equivalent values from table 2.1. These are:
 - a) Briefcase bomb (23kg)
 - b) Sedan (454kg)
 - c) Passenger van (1814kg)

By default, a passenger van will be used, simulating the Thisday Newspaper bombing discussed earlier.

2. **Standoff distance:** This will be considered for each of the three load cases. A series of iterations will be made to find distances at which each explosive would not cause structural failure. Safe distances will be recommended for each load case. For cars and vans, these distances will be where traffic barriers are recommended.
3. **Openings:** Space will be made in the wall for a door and two windows.
4. **Boundary Conditions:** Where other parameters are being varied, the wall will be considered as freestanding. The base alone will be considered as fixed.
5. **RC column in the middle of the wall.**

The first model will be masonry alone. All subsequent models will be in a reinforced concrete frame because that is how most masonry in Nigeria is. The five variables outlined above will be explored and the response of the structure in each case will be discussed. The resulting displacements and

stresses are the main parameters that will be examined. In each case, standoff distance will gradually be reduced until the structure fails according to any of the two failure criteria. The two failure criteria from section 2.6 should be kept in mind. The displacement criterion of length/125 translates to 24 mm, while the stress criterion is sandcrete's breaking strength of 2.5 MPa. Where any one of these values is exceeded, the structure is deemed to have failed.

After this, two **mitigation measures** will be applied: These are:

- Reinforcing masonry with steel bars
- Applying carbon fibre retrofit

Finally, these two will be combined in one model. Below is a list of the models built on Abaqus.

- Model 1 (Sandcrete alone)
- Model 2.1 (Sandcrete in RC frame)
- Model 2.2 (Fixed-Fixed condition)
- Model 2.3 (A door and two windows)
- Model 2.4 (RC column in middle of wall)
- Model 2.5 (Variation of loading)
- Model 2.6 (Variation of standoff distance)
- Model 3.1 (Internal reinforcement with steel bars)
- Model 3.2 (Carbon fibre retrofit)

All models are sandcrete in a reinforced concrete frame except Model 1. Pressures were obtained using equations 2.3 and 2.4.

Table 3.2: Change in pressure with size of explosive

Size	R (m)	TNT Mass (kg)	Z	Ps (>10Bar)	Ps (0.1<Ps<10Bar)	Pressure (Pa)	Pressuere (kPa)
Briefcase Bomb	5	23	1.8	2.2	1.9	18796.7	18.8
Sedan	5	454	0.7	25.3	28	280114.8	280.1
Passenger Van	5	1814	0.4	98.2	108.4	1083693.5	1083.7

Table 3.3: Safe standoff distances in each model

Loading Situation	Model	R (m)	TNT Mass (kg)	Z	Ps (>10Bar)	Ps (0.1<Ps<10Bar)	Pressure (Pa)	Pressure (kPa)
Passenger van	Model 1	10	1814	0.8	13.2	14.4	131538	131.5
Passenger van	Model 2.1	14	1814	1.1	5.4	5.7	56595.3	56.6
Passenger van	Model 2.2	16	1814	1.3	4	4	39593.6	39.6
Passenger van	Model 2.3	11.5	1814	0.9	9	9.7	97279.2	97.3
Passenger van	Model 2.4	10	1814	0.8	13.2	14.4	131538	131.5
Passenger van	Model 3.1	10	1814	0.8	13.2	14.4	131538	131.5
Passenger van	Model 3.2	6.4	1814	0.5	47.4	52.4	473630.7	473.6
Passenger van	Model 3.3	6.3	1814	0.5	49.6	54.9	496060.6	496.1

MODELLING AND RESULTS

4.1 Model 1: Masonry Alone

Figures 4.1, 4.2, 4.3 and 4.4 show the model, the displacement contour, the sideward view of the displacement and the stress contours on the wall respectively.

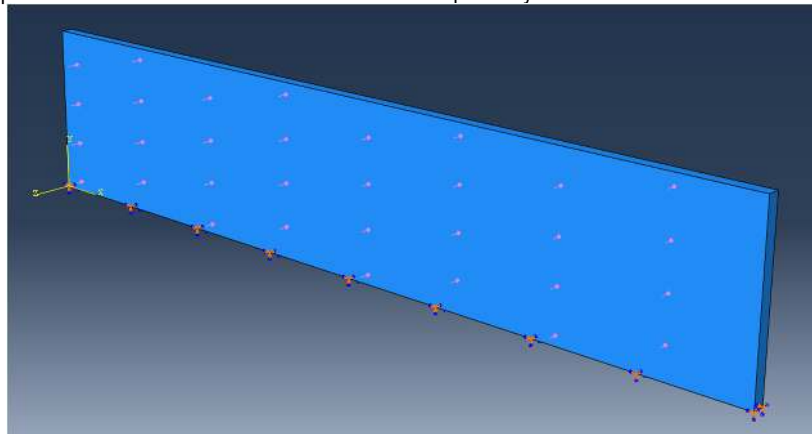


Figure 4.1: Model 1 in Abaqus. The base alone is fixed

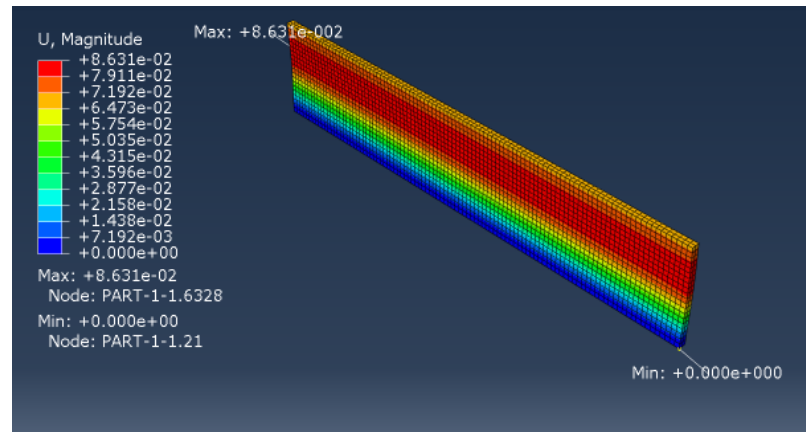


Figure 4.2: Displacements in Model 1

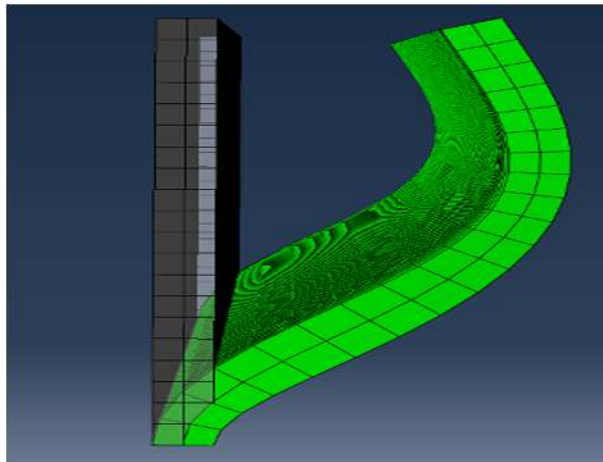


Figure 4.3: Cantilever displacement of Model 1

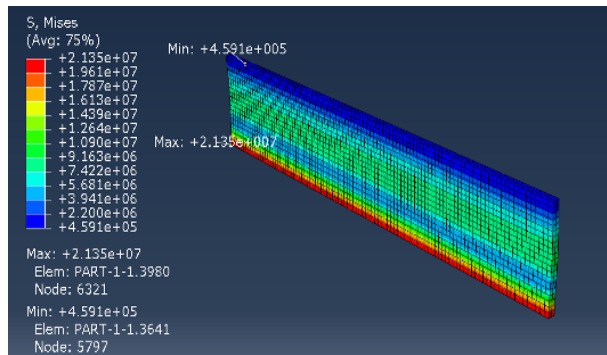


Figure 4.4: Stresses in Model 1

Model 2.1: Masonry as Infill in Reinforced Concrete

From this section on, masonry will be modelled as infill in reinforced concrete frames as this is how it most commonly is in Nigeria. The structure is modelled under the same conditions as Model 1 and then a series of

variations are made. Model 2.1 is the model with all the default values. All subsequent models will be discussed in relation to it. The structure to be modelled is shown on Figure 4.5. Figures 4.6 and 4.7 show the displacement and stress distributions respectively.

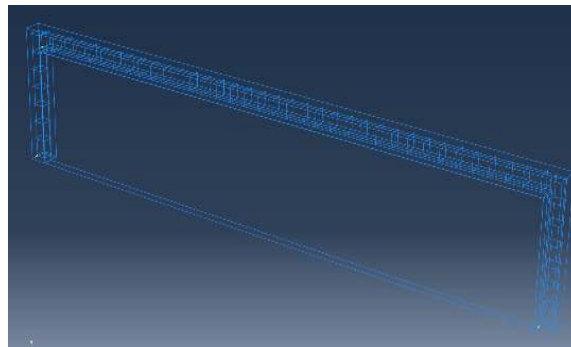


Figure 4.5: Model 2.1 in wireframe render on Abaqus

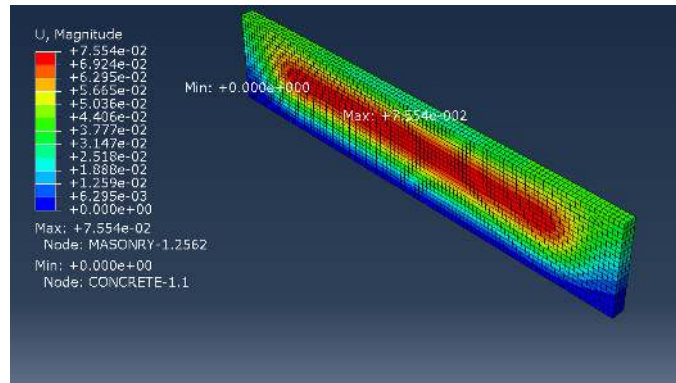


Figure 4.6: Displacements of structure in Model 2.1

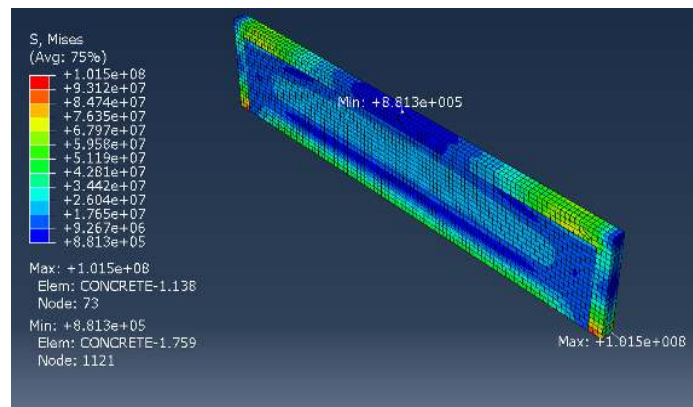


Figure 4.7: Stress distribution in Model 2.1

Models 2.2, 2.3 & 2.4

Figures 4.8 through to 4.14 show the displacement and stress distributions in models 2.2, 2.3 and 2.4.

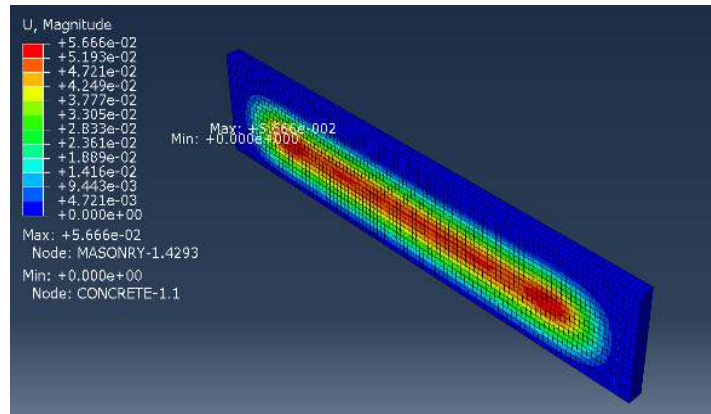


Figure 4.8: Displacement contours of Model 2.2

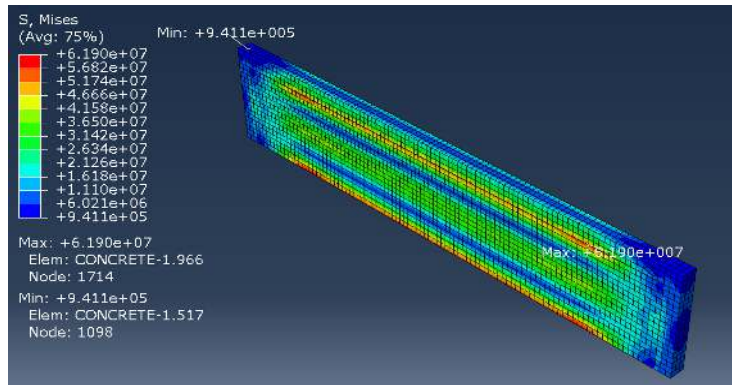


Figure 4.9: Stresses in Model 2.2

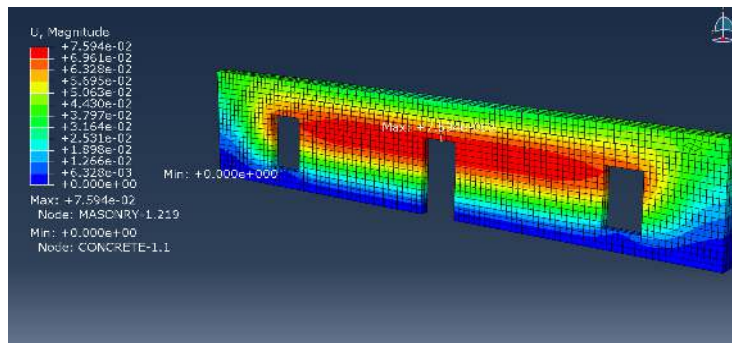


Figure 4.10: Displacement distribution in Model 2.3

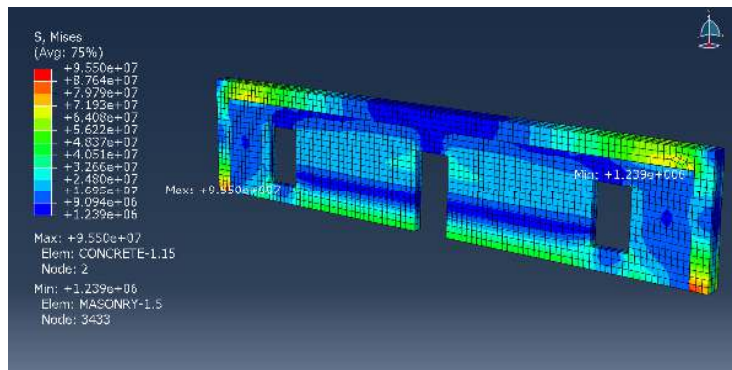


Figure 4.11: Stress distribution in Model 2.3

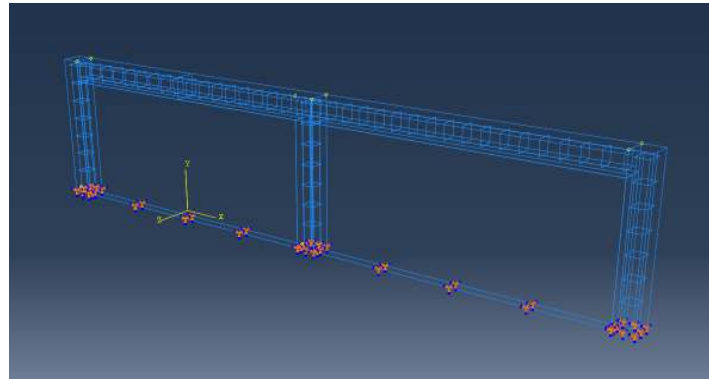


Figure 4.12: Model 2.4 in wireframe render in Abaqus

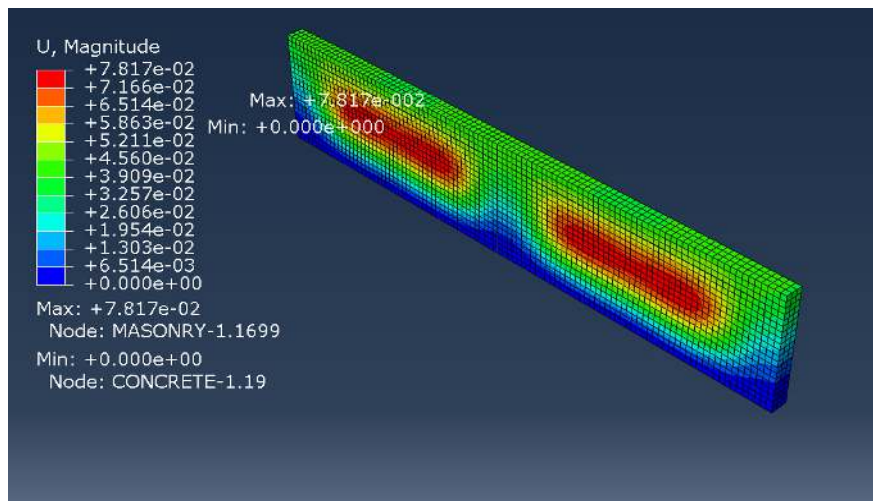


Figure 4.13: Distribution of Displacements in Model 2.4

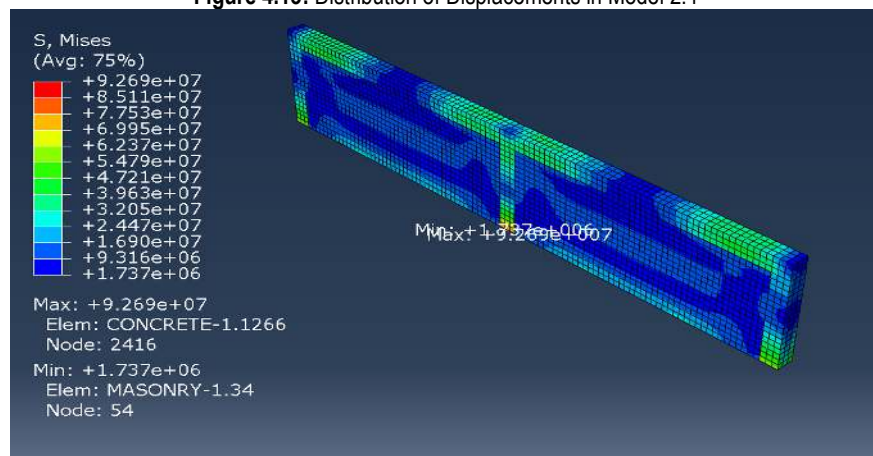


Figure 4.14: Stresses in Model 2.4

Model 2.5

Model 2.5 is about the variation of loading. Table 4.1 shows the variation of pressure for different load scenarios. Figures 4.15 and 4.16 show the distribution of displacements and stresses respectively. Figure 4.17 shows the changes in maximum displacement caused by the different loads.

Table 4.1: Resultant pressures for different sizes of explosives

Size	R (m)	TNT Mass (kg)	Z	Ps (>10Bar)	Ps (0.1<Ps<10Bar)	Pressure (Pa)	kPa
Briefcase Bomb	5	23	1.8	2.2	1.9	18796.7	18.8
Sedan	5	454	0.7	25.3	28.0	280114.8	280.1
Passenger Van	5	1814	0.4	98.2	108.4	1083693.5	1083.7

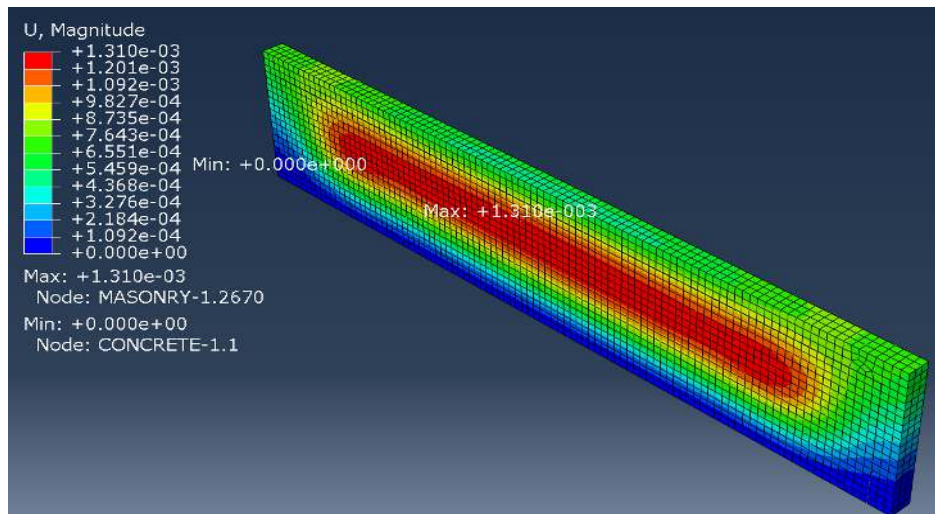


Figure 4.15: Displacements in Model 2.5 (Briefcase bomb at 5m distance)

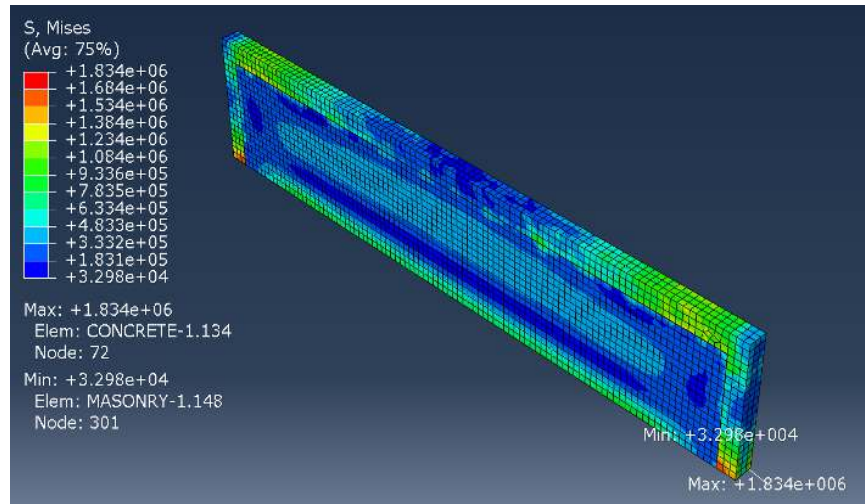


Figure 4.16: Stresses in Model 2.5 (Briefcase Bomb at 5m distance)

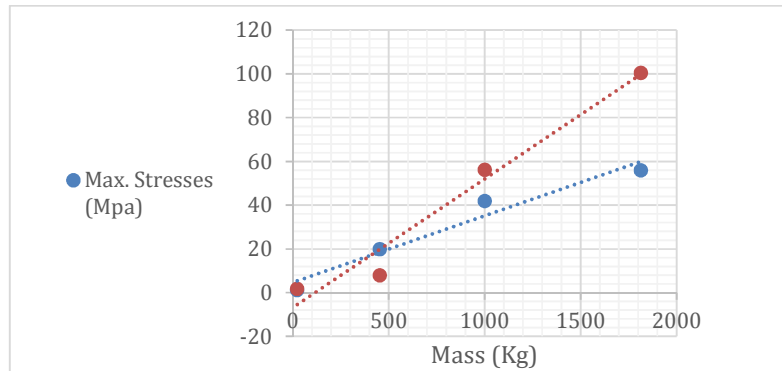


Figure 4.17: Change in displacements and stresses with increased loading

Model 2.6

Model 2.6 aims to derive the safe standoff distances of each loading case. Table 4.2 shows these.

Table 4.2: Safe standoff distances for each explosive size

Loading Situation	R (m)	Mass in TNT (kg)	Z	Ps (>10Bar)	Ps (0.1<Ps<10Bar)	Pressure (Pa)	kPa
Briefcase Bomb	5	23	1.8	2.2	1.9	22328.0	22.3
	3.5	23	1.2	4.6	4.7	46919.4	46.9
	3.2	23	1.1	5.7	6.0	59749.0	59.7
Sedan Car	5	454	0.7	25.3	28.0	253344.0	253.3
	8	454	1.0	6.9	7.4	73951.8	74.0
	8.65	454	1.1	5.7	6.0	59715.3	59.7
Passenger Van	5	1814	0.4	98.2	108.4	1083693.5	1083.7
	10	1814	0.8	13.2	14.4	144213.7	144.2
	13.75	1814	1.1	5.7	5.9	59432.1	59.4

Mitigation measures (Models 3.1 & 3.2)

Model 3.1: Reinforcing with steel

The arrangement, displacements and stresses for Model 3.1 are shown in Figures 4.18, 4.19 and 4.20.

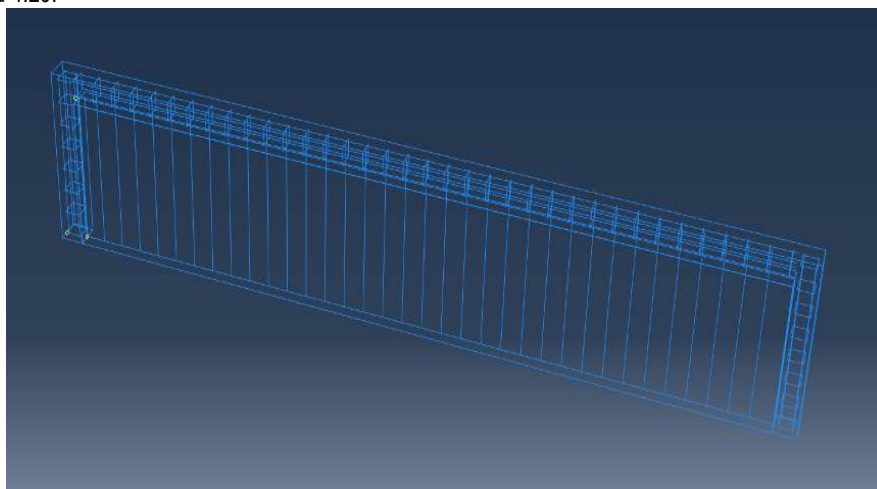


Figure 4.18: Model 3.1 in wireframe render on Abaqus

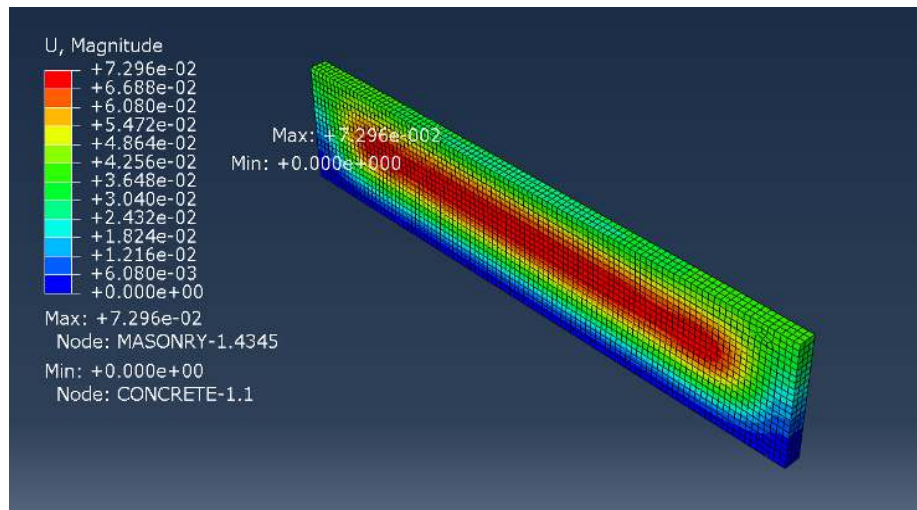


Figure 4.19: Displacements in Model 3.1

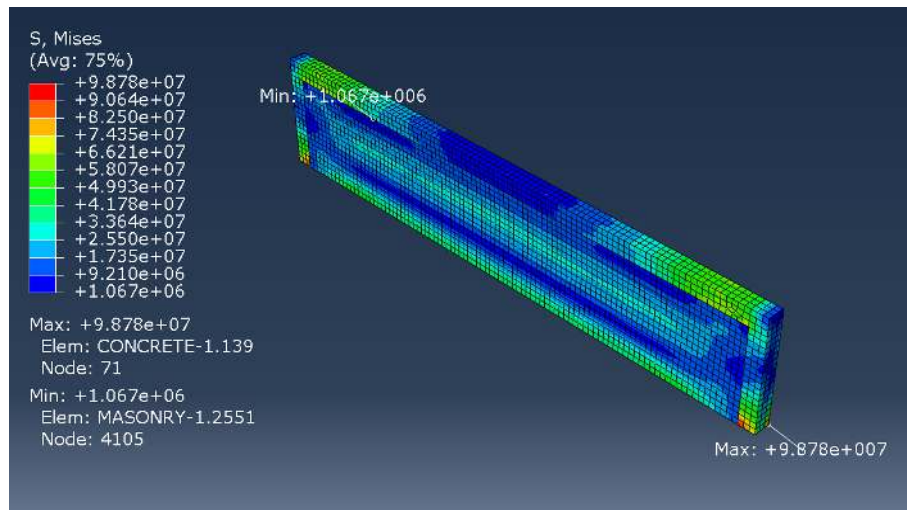


Figure 4.20: Stresses in Model 3.1

Model 3.2: Reinforcing with Carbon Fibre

Carbon fibre is modelled as a “skin” on Abaqus, as done by Pereira (2005). A Thickness of 6mm is used. The carbon fibre is attached to the structure as shown by the

maroon coloured regions in Figure 4.21a-b, while the obtained displacements and stresses are shown in Figures 4.22 and 4.23 respectively.

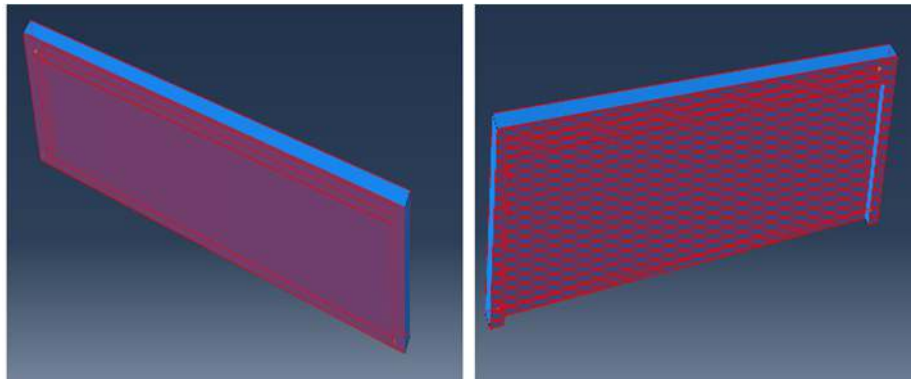


Figure 4.21a-b: Front and back views of structure. CFRP “skin” is coloured maroon

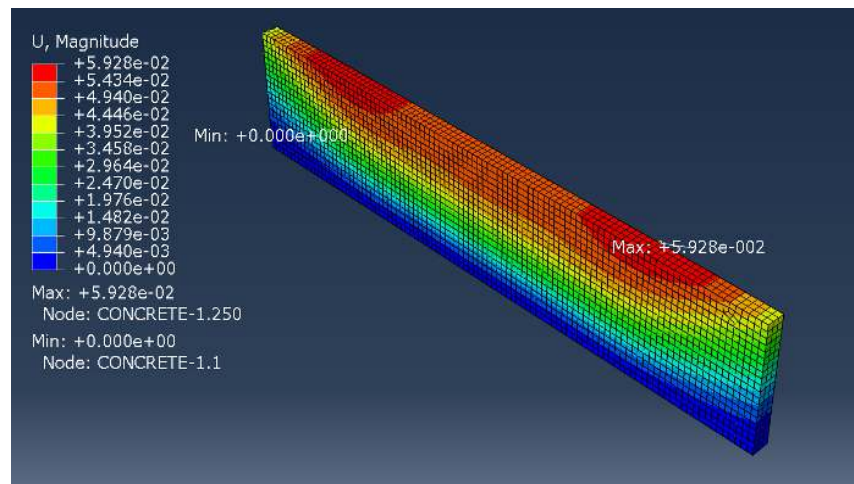


Figure 4.22: Displacements in Model 3.2

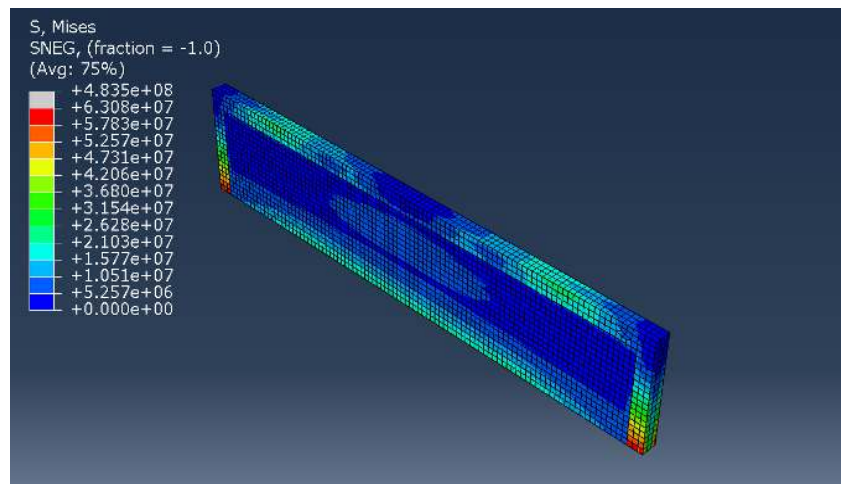


Figure 4.23: Stresses in Model 3.2

DISCUSSION OF RESULTS

There are a few noteworthy common themes observed in all the models. One such common feature is the disappearance of the cantilever distribution of stresses and strains in the freestanding wall after Model 1 (masonry alone). In subsequent models, this cantilever distribution is offset by the introduction of the reinforced concrete frame. The difference in the stiffness of sandcrete and concrete is significant enough to make concrete behave as a semi-rigidity in relation to sandcrete. The masonry infill's boundary conditions are effectively fixed at the top and bottom. This results in bulb-shaped contours with maximum displacements occurring in the middle. The notable exception to this is Model 3.2 with carbon fibre. As the fibre covers all of the structure, the structure behaves as if it has a uniform stiffness. Model 3.2 therefore behaves as a cantilever would.

The introduced concrete frame reduces displacements but increases overall stresses in the wall because it constrains movement. It should be remembered that preventing materials from deforming increases applied stresses. The concrete frame therefore makes the displacement failure criterion better but worsens the stress criterion. The concrete frame makes the wall safer in that reduced displacements should reduce the speed at which debris flies off a wall. On the other hand, not having a concrete frame means having less overall stresses and therefore less chances of structural collapse of the masonry infill. It should be noted that the infill would collapse alone, leaving the concrete frame standing in most cases as seen in the Thisday bombing (see Figure 5.1).



Figure 5.1: Rubble from Office Bombing (Adekunle, 2012), Thisday Newspaper

It was noticed that the stress failure criterion was consistently more critical as the constrained base of the sandcrete easily crushed under explosive loading. While failure in displacements stopped occurring under 8m in all models, failure in stress was over 10m in all but the carbon fibre model. The ease with which failure in stress occurs calls into question the validity of USACE's displacement failure criterion with respect to sandcrete. It can be

surmised from the models that long before displacements equal the thickness of sandcrete (225 mm), all of the wall would have failed in stress, leading to complete collapse. This is because sandcrete's strength of 2.5 MPa is very low. The Eurocode 6 limit of 24 mm used in this study is a much more realistic criterion for sandcrete.

The aforementioned weakness of sandcrete highlights the importance of the



standoff distance parameter. At some point, all the models run fail structurally because of this weakness. The lowest recorded safe standoff distance was 6.4m in Model 3.2. These safe distances can potentially be used by designers and planners when determining the position of traffic barriers with respect to buildings.

With the lowest safe standoff distance, the carbon fibre model is by far the best performing. A significant note is that although it has been assumed to fail when displacements exceed 24 mm, it would not do so in reality. The fibre's adhesive bond to sandcrete would prevent it fragmenting into pieces and flying off as debris. The real safe standoff distance may be less than the 6.4m adopted in the study. The important point is that

it has been established that fibre retrofitting is one of the most effective methods of mitigating against blast loading. Reinforcing masonry with steel also did lead to improvements in both displacements and stresses, but it was only marginally better than when masonry was already put as infill in a reinforced concrete frame.

Table 5.1 shows the results obtained from Models 2.5 and 2.6 in which the size of explosive and the standoff distance were varied. Predictably, these two variations only amplified the effects of the explosive but retained the same pattern. Resultant displacements and stresses were unsurprisingly found to increase approximately linearly with the size of an explosive.

Table 5.1: Results from Models 2.5 and 2.6

Size of Explosive	Maximum Displacement (mm)	Maximum Stresses (MPa)	Comment at 5m standoff distance	Safe standoff distance (m)
Briefcase (23 kg)	1.3	1.83	Does not fail	3.2
Sedan (454 kg)	20	8	Displacements and stresses are excessive	8.65
Passenger van (1814 kg)	75.54	101.5	Displacements and stresses are excessive	13.75

Table 5.2 summarizes the displacements and stresses obtained from the models, their failure modes and the safe standoff distances in each case.

Table 5.2: Summary and comparison of Model Result Discussions



Model		Displacements	Stresses	Comment	SAFE DISTANCE (m)
(Sandcrete Alone)	Model 1	Cantilever distribution with zero at bottom and maximum of 86.31 mm at top.	Cantilever distribution with maximum of 21.35 MPa at the bottom.	Displacements and stresses are excessive. Stress more critical.	10
(Sandcrete in RC frame)	Model 2.1	Concrete behaves as a semi-fixity in relation to sandcrete. The displacement contour is bulb shaped with maximum values in the middle. The maximum displacement is 75.54 mm.	Stress contour is also bulb shaped, although less pronounced. Maximum stress is 101.5 MPa at the base of concrete columns. Maximum stresses in sandcrete are at the base and exceed 30 MPa.	Stress more critical. Displacements and stresses are excessive.	14
(Fixed-Fixed boundary condition)	Model 2.2	Similar to Model 2.1 but no displacements at top due to fixity. Also bulb-shaped contours with maximum of 56.66 mm in middle of masonry.	Has the greatest distribution of stresses on average with most of masonry being subjected to over 30 MPa.	Displacements and stresses are excessive. Stress more critical.	16
(A door and 2 windows)	Model 2.3	Similar to Model 2.1 but has a more distorted bulb pattern because of the openings. The maximum displacement is 75.94mm at the top of the door.	Also close to Model 2.1. The maximum stress is 95.5 MPa in the concrete beam.	Displacements and stresses are excessive. Stress more critical.	11.5
(RC column in middle of wall)	Model 2.4	2 bulb patterns on either side of the introduced column because it behaves as a semi-fixity. The maximum value is 78.17mm in the middle of each bulb	Same pattern as 2.1 but split into two because of the column. The maximum stress is 92.69 MPa in concrete. Over 30 MPa in Sandcrete base.	Displacements and stresses are excessive. Stress more critical.	10
MITIGATION MEASURES					
(Internal reinforcement with steel bars)	Model 3.1	Follows same pattern as Model 2.1 but maximum is slightly less at 72.96 mm	Follows same pattern as Model 2.1 but maximum slightly less at 98.78 MPa in concrete. Stresses exceed 30 MPa in sandcrete base.	Displacements and stresses are excessive. Stress more critical.	10
(Carbon fibre retrofit)	Model 3.2	Similar to Model 1 as it behaves as a cantilever. Maximum displacement is 59.28mm at top.	Maximum stresses are around 63 MPa in column bases. Stresses at base of sandcrete are around 15 MPa	Displacements and stresses are excessive. Displacement more critical.	6.4

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to not only model the response of sandcrete under blast loading but to explore and recommend tangible measures to protect people and minimise damage from blast loads. It is important to note a few limitations of the modeling in this study so that progress can be made in the future. Though a homogeneous model was used, a heterogeneous model of masonry is more representative of reality as the interfaces between mortar and units are often weak spots. Moreover the interface between masonry and concrete should be defined by relevant parameters such as breaking strength and friction coefficients so that failure there can be observed. In addition to these interfaces, simulating the breaking up of the structure into debris would lead to interesting findings. In this study, displacements have been used to infer the amount of debris from each simulation. Future work should take this further and use more direct methods to model debris from sandcrete. Finally, hollow sandcrete blocks should be modelled instead of the solid blocks in this study because they are more widespread in Nigeria.

Despite these limitations, it is maintained that the results obtained are a good starting point for future research and a number of important findings can be surmised from the study. The validity of the modeling in this study

lies not so much in the accuracy of each model as in the comparisons between them. Moreover, common themes emerged for which reasonable explanations could be found. For example, it was found as expected that sandcrete alone and as infill in reinforced concrete frames fails under common terrorist explosions such as car bombs. It was recognized that taking structural measures is not always possible as they are costly. For this reason, safe standoff distances were found for each loading scenario. These distances can be used when determining the location of traffic barriers from buildings.

Of the mitigation measures, carbon fibre retrofitting was found to be far more effective than reinforcing masonry with steel. The advantages of fibre-reinforced polymers in general are many. In fact, although a failure standoff distance of 6.4m was found for the carbon fibre model due to the displacement limit, the structure would likely not fail in reality because of the adhesive bonding of the polymer. Given that bombs blasts are a relatively new phenomena in Nigeria, the fact that carbon fibre can be readily applied on existing structures makes it even more appealing.

It should be noted that carbon fibre strips are expensive and so are usually applied in strips, not covering the whole structure as in this study. Feasibility studies on the use of carbon fibre and other polymers such as aramid



and glass in Nigeria should be carried out so as to guide studies such as this. Although more needs to be done in this regard, Markson et al. have explored the potentials of bamboo polymer, a cheap and locally available material, so optimism would not be unjustified (2015).

In summary, promising results were obtained showing the importance of two factors: using fibre reinforced polymers and safe standoff distance. Applying polymers was found to be the most effective method of increasing sandcrete's resistance to explosions. However, as sandcrete is a weak material and polymers are expensive, the safe standoff distance obtained from iterations is also important. These safe distances can be used in determining the locations of traffic barriers. Finally, physical tests should be carried out to verify the validity of this modelling.

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