The Impact Response of Coquina: Unlocking the Mystery Behind the Endurance of the Oldest Fort in the United States

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Abstract The Castillo de San Marcos fort in St. Augustine, FL, has withstood numerous wars and hurricanes for over 300 years. Interestingly, during military sieges it was discovered that the fort walls did not shatter upon impact, but instead absorbed the cannonballs. The endurance of this fort is attributed to a native rock, called coquina, from which it was constructed. Quasi-static and high strain rate uniaxial compression experiments were conducted on coquina and two other materials (sandstone and a structural foam) with similar structures and physical properties. Additionally, low-velocity ball impact experiments, analogous to impacts due to cannonballs, coupled with high-speed imaging were performed to investigate the impact response. The analysis explored the operative deformation mechanisms which gave rise to the fort's endurance against impacting cannonballs. It was revealed that the microstructure of coquina does not lend itself to macroscopic brittle fracture, but absorbs impact energy by progressive crushing similar to a cellular structure, and thus allows for a high specific energy absorption.

Keywords Coquina · Energy absorption · Ball impact · Castillo de San Marcos

Introduction

The Castillo de San Marcos fort in St. Augustine, Florida, is the oldest masonry fort in the continental United States and has been standing for more than 330 years [1]. Some exterior and interior views of the fort are presented in Fig. 1. Originally constructed by the Spanish between 1672 and 1695, it has endured numerous wars and incursions during its long tenure (1700–1900) and has even weathered several hurricanes [2]. Amazingly, during the many battles, the fort was never taken by force. In fact, impact impressions resulting from the cannonballs firing on the fort wall can still be seen to this day (see Fig. 2a, b). The thickness of the fort wall ranges from 12 to 19 feet, with thicker construction on walls facing the harbor which were more susceptible to cannon fire. Realizing its extraordinary ability to absorb impacting projectiles, soldiers would even use the fort walls for target-practice. Interestingly, the damage caused to the walls did not result in large brittle cracks, but only holes as the projectiles (cannonballs and bullets) were captured by the fort walls (see Fig. 2a, b).

The extreme durability and endurance of the fort has been attributed to a unique indigenous rock, called 'coquina', from which the fort walls were constructed. Unlike other structural materials of the day (e.g. stone), when the cannonballs impacted the fort walls, the coquina absorbed the impact without causing large cracks or catastrophic failure of the wall (see Fig. 2a, b). Instead, the cannonballs became embedded several inches deep into the wall, with no large cracks emanating from the impact site or fragments being ejected from the wall. Coquina is a partially lithified sedimentary rock, found abundantly along the east coast of Florida, that contains many pores and is relatively soft when quarried [3]. This makes coquina easily shaped for structural usage. The fact that it hardens when exposed to air is a

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Fig. 1 **a** and **b** Images of exterior and **(c, d)** interior construction of the Castillo de San Marcos fort

Fig. 2 Images of the walls at the Castillo de San Marcos illustrating the residual **a** bullet and **b** cannonball holes. Notice the localized nature of the damage in **a** and **b** due to projectile impacts. No cracks are seen to radiate away from the impact crater. **c** An image of the coquina microstructure and **d** a high-magnification image revealing the shell fragments and porous, heterogeneous structure

discovery which prompted the Spaniards to quarry the soft rock to build the Castillo de San Marcos fort. A typical microstructure of coquina is shown in Fig. 2c and d. Coquina is primarily made up of crushed shell, fragmented fossils and coral, limestone, sand, minerals and clay [1]. The word ‘coquina’ has its roots in the Spanish word for

cockleshells or shellfish meaning “tiny shells” [4, 5]. The rock used in the fort was originally quarried by the Spanish almost 400 years ago from the King’s Quarry on Anastasia Island, which has since become Anastasia State Park. The coquina found in the Anastasia formation includes rock formed during the Late Pleistocene Epoch

($\sim 12,000$ – $110,000$ years ago) [6], but may include deposits from all three interglacial stages [7].

Every year the fort has around 750,000 visitors, including students, but little scientific explanation is available about the unique behavior of coquina. Surprisingly, to date, no systematic studies have been performed to understand the extraordinary deformation behavior of coquina. Only one study by Knab and Clifton [8] is available which determined properties such as static compressive and flexural strength, dry density, and water absorption of coquina. With this motivation, the current study examines the static and dynamic mechanical response of coquina rock by uniaxial compression and low-velocity ball impact experiments. For comparison, sandstone, a structural material and sedimentary rock with high porosity and loosely bonded sand particles, and a modern-day commercial foam with high level of uniform cellular porosity, were also investigated. The focus is to characterize the fracture behavior and energy absorption capacity of coquina and to compare its behavior with sandstone and cellular foam. Finally, the operative deformation mechanisms in coquina, which enabled the fort's extreme durability against impacting cannonballs, are discussed.

Materials

Coquina samples of size $10.5\text{ cm} \times 8.5\text{ cm} \times 2.2\text{ cm}$ were purchased from the Castillo de San Marcos gift shop. This coquina was quarried from Summer Haven, FL, located about 10 miles south of the original quarry on Anastasia Island, which is now a protected historic site. To gain a better insight into the deformation behavior of coquina, another sedimentary rock, sandstone, and a cellular foam were procured. Sandstone is composed of minerals such as silica, feldspar and calcium carbonate [4, 9]. Sandstone is formed from rock grains or mineralic crystals which are typically cemented by calcite, clay, and silica. Its microstructure consists of a high volume fraction of intragranular porosity (see Fig. 3a). The cellular foam was selected due to its

uniform porosity and cellular structure (see Fig. 3b). This material is a structural polyvinyl chloride (PVC) foam which was expected to provide the response of an ideal cellular structure [10] and acted as a reference to understand the response of the previous two natural materials.

Experimental Method

Experiments were conducted under three loading conditions: (1) quasi-static uniaxial compression, (2) dynamic uniaxial compression, and (3) low-velocity ball impact. The quasi-static compression experiments were performed using a servo-hydraulic machine (MTS model 309.2, Eden Prairie, MN USA) with a displacement rate of 0.1 mm/s (nominal strain rate of $10^{-2}/\text{s}$). The surfaces in contact with the test specimens were lightly lubricated in order to mitigate any frictional effects. The stress–strain curves were determined by measuring load and displacement from quasi-static tests for each material and the area under the curves, which represents the energy absorbed per unit volume (energy density or specific energy) during deformation, were then computed. Additionally, the deformation and fracture modes observed for each type of specimen were captured in situ using a digital video camera (Olympus model E-450 digital SLR, Center Valley, PA, USA).

Dynamic tests in the strain rate range of $10^2/\text{s}$ were conducted using a split-Hopkinson pressure bar (SHPB) made of high-strength maraging steel bars (VascoMax C-350). In this method, 1-D stress wave propagation principle is used to load a specimen in order to extract high strain rate deformation behavior of the test material. This testing method is well-established in high strain rate literature [11] and hence only a brief discussion is provided here. The SHPB consist of two slender metallic bars called the incident and transmission bars, and the specimen is held in between these two bars. The incident bar was 1219 mm in length, the transmission bar was of 914 mm in length, and both bars were 19.05 mm in diameter. The

Fig. 3 Representative microstructure of **a** sandstone and **b** PVC foam

Table 1 Specimen dimension used for the compression and impact testing

Material	Bulk density (g/cc)	Nominal specimen dimensions (mm) $w \times b \times h$ or $d \times h$		
		Quasi-static compression	Dynamic compression	Ball impact
Coquina	1.37–1.55 [8]	$15 \times 17 \times 21$	$16 \times 16 \times 7$	$105 \times 85 \times 22$
Sandstone	1.94–2.7 [13]	17×31	17×31	45×20
Foam	0.08–0.13 [14]	$18 \times 18 \times 26$	$13 \times 14 \times 7$	$82 \times 82 \times 25$

striker bar (254 mm in length) was launched from a gas cylinder, which then impacted the incident bar. The impact generates a uniaxial stress pulse, which travels down the long bar towards the specimen and causes the desired uniaxial compression loading of the specimen over ~ 100 microseconds. Strain gages mounted on the incident and transmission bars captured the incident, transmitted, and reflected waves. A 1-D wave analysis was performed to translate the strain gage data into the corresponding stress–strain response [11].

The specimens dimensions used for quasistatic and dynamic testing are provided in Table 1, where h is the direction of compression or impact. For quasistatic testing, long specimens with length to diameter (or width) ratio of approximately 1.4–1.5 were used. For dynamic testing similar specimen sizes were appropriate for the sandstone which has relatively high wave speed and strength. However, for extremely low-density, low-modulus materials such as foam and coquina, the specimen dimension along the length has to be reduced significantly to obtain stress equilibrium during the testing process. Stress equilibrium ensures that the stress at both ends of the specimen is the same so that uniaxial and uniform stress conditions prevail in the specimen during testing. Low-density and low-modulus (and hence low-wave speed) specimens have slow wave velocities and therefore, take longer time for stress equilibrium to be achieved. It was established by Ravichandran and Subhash [12] that it takes at least four roundtrip travel times to ensure stress equilibrium. Accordingly, the specimen dimensions for coquina and foam were reduced compared to the sandstone. The stress and strain in the specimen were calculated from the established equations for SHPB analysis [11]. In addition, the procedure for dynamically testing brittle materials, i.e., momentum trapping and pulse shaping, was followed. Lastly, the bar surfaces in contact with each specimen were lightly lubricated to minimize frictional effects.

Finally, ball impact testing was performed to mimic cannonball impact on the fort walls. For ball impact testing, large samples of each specimen were held in front of the barrel of a gas gun and a steel ball of 8 mm diameter (S2 tool steel) was propelled at a velocity of around 50–75 m/s. The normal incidence impact event was captured by a high speed camera (Vision Research® Phantom v710®, Wayne, New Jersey, USA) at up to 200,000 frames per second. The

specimen dimensions for the various tests are provided in Table 1.

Results

Quasi-Static Compression

Compressive Strength

The typical engineering stress–strain responses for coquina, sandstone, and foam from the quasi-static compression tests are shown in Fig. 4. In general, the stress–strain curves for all the materials reveal linear response up to their peak compressive strengths. Sandstone, exhibited a medium compressive strength of 46.8 ± 3.2 MPa. On the other hand, the coquina had a very low strength of 5.6 ± 0.6 MPa. The commercial cellular foam had a peak strength of around 2.8 ± 0.03 MPa. Similarly, it was determined that the elastic moduli for the coquina and foam (151 ± 17 and 99 ± 0.3 MPa) were an order of magnitude lower than that of the sandstone (4404 ± 20 MPa). The low modulus along with low-density of coquina are primarily due to its highly porous microstructure and weak bonding of the constituent particles. The above values are summarized in Table 2.

Once the peak strength was reached, both coquina and sandstone experienced a sharp drop in strength (typical of brittle failure). The sandstone failed catastrophically at only ~ 1.5 % strain and the strength dropped sharply to zero after reaching its maximum compressive strength of 46.8 MPa (see Fig. 4a and b). On the contrary, after reaching its peak strength coquina displayed continued deformation at a residual strength close to 0.9 ± 0.1 MPa (16 % of peak strength). This deformation continued in an oscillatory manner over a large strain as seen in Fig. 4c. Thus, coquina was able to sustain applied loads over a strain up to ~ 50 %. This behavior can be treated as a pseudo-ductility which enhances its energy absorbing capacity. Finally, beyond the peak strength of the foam, continued deformation at approximately a constant strength of ~ 3.0 MPa ensued over a large strain range similar to coquina (see Fig. 4d). Comparing the mechanical behaviors of coquina and foam, one can see that these materials exhibit ‘ductility’ and the ability to sustain load (i.e., residual strength) when stressed beyond their peak strength.

Fig. 4 **a** Representative stress–strain response for the three tested materials and separately illustrated stress–strain curves for **b** sandstone, **c** coquina, and **d** foam under static uniaxial compression. Each plot indicates maximum compressive strength (σ_{max}), residual strength (σ_{res}), if applicable), elastic modulus (E), and the energy consumed per unit volume (i.e., specific energy or energy density, U^*)

Table 2 Properties of the three materials during static and dynamic compression testing

Material	Young's modulus (MPa)	Strength (MPa)		Specific energy (J cm^{-3})	
		Static compression	Dynamic compression	Static compression	Dynamic compression
Sandstone	4404 ± 20	46.8 ± 3.2	87.6 ± 1.9	$0.29 \pm 0.05^*$	$0.12 \pm 0.07^*$
Coquina	151 ± 17	5.6 ± 0.6	8.3 ± 1.8	$0.59 \pm 0.18^*$	$0.11 \pm 0.02^*$
Foam	99 ± 0.3	2.8 ± 0.03	2.4 ± 0.7	$1.25 \pm 0.05^{**}$	$1.11 \pm 0.05^{**}$

* Calculated for strain levels shown in the stress–strain curves

** Calculated for a strain level of 0.5

Deformation Mechanisms

In order to elucidate the deformation mechanisms responsible for the observed stress–strain behavior, the in situ damage during quasi-static loading was captured by time-lapse photography (see Fig. 5). By examining the deformation characteristics during testing, clear differences in the failure behavior between the sandstone, coquina, and foam were observed and correlated to the strength and energy absorption capabilities of the materials. In the case of both the sandstone and coquina, as the applied force reached a maximum, several cracks were first initiated near the loading surfaces. For sandstone, several dominant cracks grew axially causing a catastrophic failure, as shown in Fig. 5a, followed by a rapid strength drop. At this point, the failure could be heard audibly, followed by large cracks

fully propagating through the entire length of the sample and a few large fragments being ejected at high velocity. This behavior in sandstone was marked by a sudden energy release during loading which was reflected in the sudden strength drop in the stress–strain data (Fig. 4b). For the coquina, the sudden strength drop, seen in Fig. 4c, occurred as the top layer and some peripheral material crumbled (localized failure), and eventually fell off (see Fig. 5b). Under increased displacement, the remaining core material continued to sustain the load until further crumbling of the peripheral material occurred. This intermittent increase and decrease in load caused progressive crushing of coquina and periodic load oscillations. Thus, rather than demonstrating a catastrophic mode of failure, the coquina exhibited progressive crushing, i.e., gradual release of strain energy. Lastly, the foam deformation was

Fig. 5 Sequence of images showing the operative fracture mechanisms during static compression testing for **a** sandstone, **b** coquina, and **c** foam. The dashed lines in **b** illustrate the virgin specimen width

characterized by localized crushing of the open foam cells near the loading surfaces. With increased displacement, further pore crushing occurred in the specimen until the foam eventually became an incompressible solid (see Fig. 5c). Thus, coquina and foam exhibited similar behaviors in terms of progressive crushing but through different energy absorbing mechanisms. In coquina, the loosely bonded shell fragments de-bonded and were crushed upon application of load, whereas, in foam, the struts of the cell walls buckled and crushed. Furthermore, the crushing behavior of the coquina is much more non-uniform due to the highly defective and heterogeneous microstructural make-up, which gives rise to oscillatory residual strength behavior, whereas the highly homogeneous porous structure in foam gives rise to a constant residual strength with continued deformation. Additionally, due to the brittle nature of the coquina, the failure process is marked by fracture and fragmentation rather than cell wall buckling in the foam.

Post-mortem fragment analysis of the test specimens, shown in Fig. 6, exemplified that the failure of the sandstone is marked by formation of long axial cracks and large

columnar fragments. On the other hand, the progressive crushing behavior of the fragmented shells in coquina led to comminution of the specimen. Lastly, the foam displayed primarily pore crushing, during which, the cellular structure collapsed, and thus resulted in a dense solid of crushed foam.

Dynamic Compression

Compressive Strength

The stress–strain responses of coquina, sandstone, and foam under dynamic compression (250, 600, and 7000/s, respectively) are displayed in Fig. 7. Similar to the static compression testing, the sandstone yielded a notably higher dynamic failure strength compared to that of the coquina, 87.6 ± 1.9 versus 8.3 ± 1.8 MPa, respectively. Additionally, the dynamic strength values for both materials were greater than their respective static strength values (see Table 2), suggesting that both materials showed strain rate sensitivity in strength for the strain rate regime examined in this investigation. This behavior is attributed to the fact that

Fig. 6 Images depicting the specimen condition after static compression test of **a** sandstone, **b** coquina, and **c** foam

Fig. 7 **a** Representative dynamic uniaxial compression stress–strain responses for the three materials and individual plots for **b** sandstone, **c** coquina, **d** foam. The associated energy consumed per unit volume values is also given

increased loading rate resulted in shorter time for cracks to initiate and grow while the applied stress continued to rise. This led to a greater compressive strength to failure. Note from the stress–strain responses in Fig. 7 that the sandstone exhibited a typical brittle failure mode (strength fell rapidly after reaching the peak value), while the coquina showed a more complex behavior. Thus, rather than failing catastrophically, the coquina showed a residual strength which is $\sim 34\%$ of the peak strength. Also, unlike the sudden drop at peak strength during quasi-static loading (see Fig. 4c), the failure was much more gradual, with residual strength oscillating between 1 and 3 MPa. Lastly, the stress–strain response for foam was found to be similar to its static compressive response (Fig. 4d). The peak strength under dynamic load was around 2.4 ± 0.7 MPa. Beyond

its elastic limit, the foam exhibited a nearly constant residual strength at almost the same peak strength. These values suggested that foam exhibits low rate-sensitivity in strength, whereas both sandstone and coquina revealed a significant increase in strength with strain rate for the examined strain rate range.

Deformation Mechanisms under Dynamic Loading

The fracture morphology under dynamic compression loading was analyzed from the high-speed images shown in Fig. 8. For the sandstone, a large number of shear-dominated cracks rapidly grew and caused a significant dilatation of the specimen. It is well known that brittle materials exhibit axial cracking during uniaxial compression loading

Fig. 8 A sequence of high-speed images illustrating the high-rate damage history during dynamic compression loading for **a** coquina, **b** sandstone, and **c** foam

[15]. This was clearly observed for the sandstone during static loading (Fig. 4), but not during dynamic loading. Due to the abundance of porosity in sandstone, multiple cracks nucleated simultaneously under dynamic loading. Instead of primarily axial crack growth, a greater number of small cracks grew at an angle, characteristic of a quasi-ductile response due perhaps to inertial confinement afforded by the increased strain rate. Additionally, the sandstone reached catastrophic failure more rapidly (less than 100 μs) compared to the coquina (more than 200 μs). This behavior is reflected in the stress–strain curves in Fig. 7, where the peak strength was reached in a shorter strain range in sandstone than in coquina. This is attributed to the greater density and elastic modulus of sandstone. The greater level of microstructural interconnectivity and stronger interparticle bonding in the sandstone allowed for rapid stress transmission during dynamic loading and higher crack propagation velocities. For the coquina, the failure occurred by multiple crack initiation and propagation similar to its static behavior where numerous cracks were initiated in the specimen periphery leading to comminution and removal of the peripheral material. This behavior is further amplified by the highly heterogeneous microstructure of the coquina (e.g., abundance of pores and particle boundaries) where the crack

path is expected to be more tortuous which delays catastrophic failure and leads to gradual softening of the entire coquina specimen as reflected in the stress–strain response in Fig. 7c. For the case of foam, the observed deformation mechanism is still crushing of the porous cells. The cell walls crumble gradually at a constant stress level over a long strain range. It appears that this deformation mechanism in foam is not strain rate dependent process because the stress level in both static and dynamic loading is almost the same (see Table 2).

Post-mortem examination of the dynamic compression test specimens, shown in Fig. 9, demonstrated enhanced fragmentation and pulverization of the sandstone compared to its static behavior. Due to rapid loading of the specimen, less time was available for long cracks to grow and propagate during dynamic loading. Thus, a large number of small cracks were formed, leading to increased comminution of the sandstone. The formation of conical fragments near the loading surfaces was the result of increase in friction between the sandstone and the steel bars under the dynamic loading. The deformation of the coquina and foam did not differ drastically from their static behaviors. Similar to static loading, coquina experienced comminution and fragmentation due to

Fig. 9 Images depicting the deformation of the **a** sandstone, **b** coquina, and **c** foam after dynamic compression testing. In **a** conical fragments (“cf”) are denoted

progressive crushing, while the foam failed by cellular crushing and compaction.

Energy Absorption

By computing the area under each stress–strain curve, the energy density, or energy per unit volume, consumed in the deformation process for each material was determined. These values are given in Table 2. During static compression, coquina had 2 times the energy absorption capability ($0.59 \pm 0.18 \text{ J cm}^{-3}$) compared to that of sandstone ($0.29 \pm 0.05 \text{ J cm}^{-3}$), but only half the absorption capacity of foam (1.25 J cm^{-3}), as seen in Fig. 4. Despite having a high compressive strength, sandstone did not absorb high energy density due to its limited strain to failure range (1.5 %) and catastrophic brittle fracture. On the other hand, coquina and foam exhibited much lower compressive strength, but deformed over a larger strain exceeding 50 %. Despite having a greater peak strength, the coquina had half the energy density of the foam due to a lower residual strength and greater strength-drop beyond its peak strength. It is worth noting that the energy density calculations are not able to capture the true energy per unit volume absorbed during the post-failure response of coquina. Due to the continuous loss of peripheral material with increased strain (see Fig. 5b), the residual strength of the coquina refers to the load sustained by the remaining central column of coquina material. However, the calculations were performed considering the original volume of the specimen. With at least half of the cross-sectional area diminishing during deformation as seen in Fig. 5b, the energy consumed is at least twice that calculated, suggesting that coquina may in fact absorb significantly more specific energy than a characteristically brittle sedimentary rock such as sandstone.

The absorbed energy densities during dynamic loading for the sandstone and coquina were calculated to be

0.12 ± 0.07 and $0.11 \pm 0.02 \text{ J cm}^{-3}$, respectively. However, the coquina spread out the impact stresses appreciably over a larger strain range. It is presumed that such a response would be preferred for mitigating impact loads, producing a “softer” response than the typical catastrophic brittle response seen for sandstone. Compared to foam, the coquina still demonstrated a reduced capacity for energy absorption during dynamic loading. This is because of the instantaneous fracture of the coquina as soon as the dynamic load was applied where as in static loading the coquina was able to sustain nearly 50 % strain due to the continuous displacement of the piston in the machine. However, the dynamic loading caused instantaneous fracture and resulted in small strain values and low specific energy absorption. The foam withstood the same level of strain and exhibited similar crushing behavior in both static and dynamic loading, and yielded almost the same energy absorption in both cases as shown in Table 2.

Clearly, foam had the largest energy absorbed during deformation followed by coquina and sandstone. The brittle fracture and large fragmentation in sandstone results in small amount of energy absorbed during the deformation, whereas, progressive material shredding in coquina gives rise to large strain and higher energy absorption, especially at quasistatic loading. Due to small specimen thickness in dynamic loading, the progressive crushing of coquina could not be observed. Finally, the energy absorbed in the foam is the greatest due to its progressive crushing and ductile stress–strain response over a large strain range. In the impact experiments, the understanding developed above will be utilized to rationalize the ball impact response of each of the materials.

Ball Impact Experiments

The damage developed in sandstone, coquina, and foam due to ball impact (analogous to a cannonball impact

Fig. 10 High speed images of ball impacts on **a** coquina, **b** sandstone, and **c** foam

event) was captured by high-speed imaging, as shown in Fig. 10. Clear differences were observed between the response of three materials. The ball impact on the sandstone at 75 m/s caused the rock to catastrophically shatter into many fragments due to the formation of a number of long cracks which appear as radial cracks on the impact surface. Upon impact, the strong bonding between the sand particles is suddenly released causing a rapid release of energy. Once structural cohesion is lost, the large fragments were ejected off. It was found that these fragments flew away at a velocity of approximately 20 m/s. At the same time, the ball rebounded at ~ 8 m/s. The images also revealed that the ball was in contact with the sandstone for less than $10 \mu\text{s}$. The impact response was more characteristic of a hard material, typically observed for brittle materials under dynamic impact. Thus, energy dissipation in the sandstone was due to nearly instantaneous fragmentation.

On the other hand, the impact of the steel ball at 60 m/s on coquina was completely absorbed by the coquina and

the ball itself was embedded in the coquina rock without forming any visible large cracks in the surrounding material at the time of the impact. Additionally, no rebound of the ball was observed. The impact response was characteristic of a soft material impact (quasi-ductile), owing to its highly porous structure (full of innumerable heterogeneous interfaces, pores, and other defects) and weak bonding between neighboring particles. Thus, as the ball advanced into the coquina, slow energy absorption occurred due to local crushing, but no large cracks were formed. Additionally, the significant particle comminution ahead of the projectile was evidenced in the high-speed images by the high-velocity ejecta which was expelled from the impact site, typical of an impact on brittle materials [16, 17]. The fine particle ejecta oppose the impacting ball and also erodes the impactor surface.

Finally, a ball impact on the foam at 82 m/s revealed that the ball was entirely absorbed and captured by the material. The ball was found to be embedded deeply in the foam without any damage extending to the surrounding

Fig. 11 Images of the impact surface of recovered steel balls after impacting **a** sandstone and **b** coquina. Pitting and scratches can be observed due to frictional contact between the impacting ball and comminuted particles of the impacted material

area. Similar to coquina, deformation was highly localized to the impact site and was accommodated by localized crushing of foam cells beneath the impacting ball.

Post-mortem analysis of the recovered steel balls gave further insight into the nature of the interaction between the debris created and the incoming projectile. The impact surface of the ball, shown in Fig. 11 revealed evidence of wear and erosion due to the debris generated from sandstone and coquina. The frictional damage to the ball appeared as radial scratches and grooves on the ball as a result of the comminuted material passing by the ball at high velocity. No wear marks were observed on the steel balls which impacted foam (not shown for brevity). In Fig. 11a minor pitting of the surface is seen due to the impact on the hard sandstone, which dulls the surface. Figure 11b shows long grooves formed due to erosive action of debris from coquina as well as fine comminuted material adhered to the ball surface. Thus, it would be anticipated that increased frictional energy dissipation in coquina would lend itself to enhanced impact performance.

Discussion

The observed cracking and fragmentation behavior of sandstone (Fig. 10a) is typical of a “brittle” material where long cracks form upon impact. Strong particle cohesion leads to relatively high compressive strength and elastic modulus, but catastrophic failure once its elastic limit is reached. The failure mode is characterized by extensive crack propagation and fragment formation. The brittleness of sandstone causes the impacted material to experience an ‘impulse’ of impact energy, resulting in catastrophic brittle failure (sudden release of particle bonds) which requires little energy. Thus, despite exhibiting superior mechanical properties (high elastic modulus and strength), the narrow

elastic strain range and brittle fracture limit the energy absorbing capacity of sandstone.

On the opposite end of the spectrum, the cellular foam displays pure crushing behavior due to a well-designed cellular structure. The deformation occurs at a constant stress over a large strain, due only to local, progressive crushing of the material. This allows extended contact time, which slowly absorbs the kinetic energy of the impactor. The ability of a material to resist the impact damage in this manner is crucial to providing superior energy absorption capabilities.

Finally, the coquina exhibits a unique failure response best described as semi-ductile (at macroscale), despite being nominally brittle (at microscale). While individual particles are crushed due to the incoming ball, collectively the coquina behaves in a quasi-ductile manner due to the weak interparticle bonding between constituents. The heterogeneous and highly porous coquina microstructure provides relatively low compressive strength and elastic modulus, which allow for easier penetration when impacted. Beyond its elastic limit, the material’s propensity towards localized progressive crushing prevents large cracks from forming during impact. Thus, significant comminution occurs ahead of the impacting ball, leading to fine particle ejecta, which opposes the incoming ball and erodes the projectile.

The results in this article are on a coquina rock recently extracted and sold in the Fort’s gift shop. However, the mechanical response exhibited during wars in the 1700 s was on a coquina which was dried, had endured numerous wet and dry seasons over a period of around 50 years, and was exposed to the weathering effects of salt water due to proximity to the ocean. It is possible that the coquina in the fort walls may have a slightly different stress–strain response and different mechanical properties than the coquina used in this study. Nevertheless, the fundamental deformation mechanisms in response to ball impacts are assumed to remain the same despite the differences in the environmental exposure.

Based on the above experiments and observations it can be concluded that the primary mechanisms of energy absorption in coquina were identified as particle debonding, fracture and fragmentation of particles, and collective progressive crushing. All these damage modes contributed to the capture of cannonballs upon impact on the fort wall during wars. Thus, the coquina benefited from its heterogeneous cellular structure, low bond strength between particles, and low fracture resistance which enabled high energy absorbing capabilities and the ability to capture cannonballs without shattering the walls. When impacted, the coquina, similar to the behavior of the foam, exhibited a superior ability to absorb 100 % of the impact energy. The improved understanding of coquina gained from this

study may be used to design and develop new lightweight, blast-resistant materials. The study also underscores the need for thorough mechanistic characterization that goes beyond the typical mechanical property determination when evaluating materials for a given application. Such information enables tailored microstructural design and optimal energy absorption during a blast or ballistic event on a structure.

Conclusions

The deformation mechanisms and energy absorbed per unit volume in sandstone, coquina, and a commercial foam during static compression, dynamic compression, and ball impact were experimentally investigated and then related to the operative mechanisms during a ball impact. It is found that brittle cracking dominates in sandstone, and large cracks emanate from the impact site causing catastrophic fracture of the rock. Hence, the energy absorbed in sandstone is the lowest among the three materials. In the case of coquina, the weak interparticle bonding and heterogeneous porosity allows for slow crack growth and gradual particle debonding during compressive loading. Upon impact, these mechanisms manifest in the form of local material crushing, which does not allow for cracks to propagate large distances, and the ball is completely captured by the material. The specific energy absorbed for coquina is almost twice that of sandstone. Finally, the homogeneous porous structure of the foam allows for crushing of the foam cells at a constant stress level over a large strain, thus absorbing the largest specific energy, among the three materials. Similar to coquina, the ball impact on foam causes local crushing of the cells and gradual deceleration and eventual capture of the ball.

The observed fundamental mechanisms of deformation fracture in coquina rock can explain the impact resistance of the Castillo de San Marcos in St. Augustine during the wars between the Spanish and the British. As the cannonballs impacted the coquina walls the mechanisms identified in the study came into play and hence cracks did not propagate long distances to shatter the fort and no large fragments were ejected from the fort walls. The energy of the impact was instead absorbed locally due to progressive crushing of the coquina. These mechanisms contributed to the ability of the

fort to endure sieges and the inclement Florida weather (hurricanes and tropical storms) over the past 300 years.

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