Ancient Adobe for Modern Sustainability: Solutions From and for Ghadames

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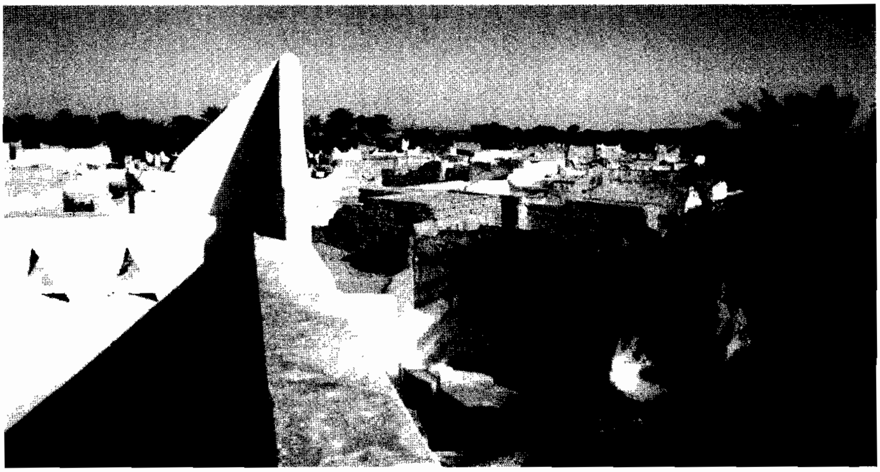
Abstract

Sustainable building principles are regularly discussed in architectural literature. Few buildings and cities, however, combine a full range of sustainable features, or enough of them to be sustainable in the long term. Old Ghadames provides an exceptional example of sustainable architecture. Ghadames is not perfect however. When only a few sustainable features become missing or lost, the future of the buildings may be put at major risk, or even the city's entire existence. In Ghadames, deficient water resource management led to a population exodus and maintenance failure. Weak adobe construction was exposed. Deteriorated buildings are susceptible to increasing adverse weather, and discourage Ghadames being re-inhabited. This paper uses Ghadames as a case study to demonstrate how particular sustainable features are effective. It shows how missing features can threaten sustainability even when they are apparently minor, and how relatively minor improvements can have a major impact on the sustainability of earth architecture. Although most lists of requirements for sustainable buildings ignore it, adaptation to changed conditions is shown to be essential for sustainability.

Keywords: *adaptation, sustainable construction, climate design, rising damp, dagga plaster, resource management*

1 Introduction

The Old City of Ghadames (OCG) in Libya, the "Jewel of the Desert" and a World Heritage site, is one of the oldest extant examples of adobe architecture. It shows that adobe construction can be a highly sustainable construction method. Adobe gives Ghadames its beauty, functionality, sustainability, and longevity, but its construction also contains detrimental aspects that have challenged and still threaten those characteristics. Ghadames was successful historically because it suited its site and prevailing conditions. Diamond (2005) identifies however, that a key determinant of sustainability and survival is the ability of societies (and their cities) to adapt to altered conditions. Over the last 35 years Ghadames has not adapted well to new conditions that have exposed weaknesses in its construction and design. To again be sustainable Ghadames needs to remedy those weaknesses and adapt to new social and environmental conditions.



Papers about Ghadames mostly focus on its unique aesthetic and thermal qualities. As an exemplar of arid region adobe architecture, its lessons are important, but are both positive and negative. These specifically adobe lessons are applicable to adobe architecture in all climates, not just arid ones, while the broader sustainability lessons are generally applicable.

Sustainable architecture design guides, such as LEED (USGBC, 2009) and the Whole Building Design Guide (WBDG, 2010), focus on: site; energy use and greenhouse gases; water conservation; environmentally benign materials; indoor environmental quality; and operation and maintenance. Additionally, general sustainability guides such as Brundtland (1987) and The Natural Step (Robert, 2002) emphasise: equity; resource efficiency; toxic substance minimization; and ecosystem protection. Alcorn (2010) highlights the significance of greenhouse gases as the key sustainability indicator, and the crucial role of long-term calculations for sustainability measurement and building performance. Diamond (2005) highlights adaptability to new conditions. A feature implicitly contained but not explicitly listed in any of these guides is the ancient dictum of Vitruvius (1914) that buildings (and cities) be not only functional and beautiful, but be solidly constructed. Fundamentally, buildings that fail are not sustainable; nor are ones which require excessive maintenance. These issues are addressed explicitly.

Ghadames scores well under all these headings as an exemplar of sustainable architecture, having survived for over 4000 years, and having some buildings that have been in daily use for at least 1300 years. But Ghadames is not a perfect example of sustainability. This paper identifies sustainability features, problems, and solutions as they apply to Ghadames.

2 Construction and Maintenance

Ghadames' hot dry climate has produced a building tradition of quickly and easily constructed adobe. The longevity of the city is testament to its sustainability. The adobe city fabric is intimately linked with several key sustainability features. But the construction and maintenance methods also present some of the biggest problems facing Ghadames' continued sustainability. Damage is evident throughout Old Ghadames, with erosion and cracking being the most apparent problems. Work undertaken by the authors under the auspices of the UNDP, UNOPS, and Libyan Secretariat of Tourism, identified several shortcomings in Ghadames' adobe methods.

Weak and erosion-prone adobe in Ghadames is adequate for its low-rainfall location when maintenance is regular, but a change to more robust adobe methods is needed now maintenance is less certain, and can reduce maintenance even if the houses are regularly inhabited. Erosion-resistant adobes are also likely to be essential for sustainable buildings as climate change increases heavy rainfall events (Schellnhuber, 2006). Even now, more than one year of rain can fall in Ghadames in one day.

As Diamond (2005) has pointed out, one essential characteristic for societies to remain sustainable is that they adapt to changing conditions and new information.

Figure 2: Detached plaster; damaged adobe substrate

For Ghadames the changing conditions of importance are climate change aggravated rain events, and reduced maintenance and construction knowledge.

2.1 Soils

A series of soil tests were undertaken, including soil composition, shrinkage, compression, and flexural strength tests. Samples were taken from quarry sources, demolished walls, and extant buildings. Some results were found to be satisfactory while some were of a lesser standard. In general, soil used for OCG adobe construction was very silty, with high sand but low clay content. Extensive enquiries about Ghadamsi building methods and history failed to find evidence of clay used for adobe. No local clay source was initially apparent. Pottery, in evidence in abandoned houses, was thought to be from another town or remote source. A pottery kiln was eventually discovered, however, on the outskirts of Ghadames. Further enquiries located clay a short distance from the city boundary, which was used for pottery but not adobe making. Abufayed, Tumi, and Elgaud (2004) indicate clay was used as a sealant in the construction of water canals, so its water resistant potential was known, but not applied to adobe making. Making adobes with better soil mixes would enable: better handling strength; adobes flat on top and bottom; more even mortar courses; and stronger walls less prone to cracking and erosion.

Organic matter was found to be common in the soils, as was a high salt content. Shrinkage rates in the initial phase of testing were acceptable, but tests showed poor compression and flexural strength. Palm fibre (coir) was incorporated in some test adobes to increase flexural strength. New Zealand and international experience indicates that using clay, and reinforcing agents such as coir or straw, greatly increases compression and flexural strength. Reinforcing agents also increase resistance to erosion and wet and dry cycling. Moisture and temperature shrinkage and expansion are also reduced (Houben and Guillaud, 1994; Standards NZ, 1998a; 1998b).

2.2 Adobe Making and Wall Construction

Ghadames' adobe bricks are made with a convex, 'turtle-back' top surface, to overcome weakness inherent in the sandy soil used. To accommodate turtle-back adobes, mortar-courses are almost as thick as the bricks. Hot dry conditions can partially dry mortar between mixing and use, reducing its effectiveness at binding adobes together. Mortar is sometimes made very wet to overcome this problem. Thick mortar-courses and wet mixes mean mortar tends to slump from the joints. Partially dried and stiff mortar does not provide adequate bedding and adhesion for the adobes. Excessively wet or dry mortar produces gaps, causing reduced wall strength, and providing pockets for rain, or eddies of sand-laden wind, to further erode the walls.

Figure 3: New trial adobes with different mixes: flat and turtle-back

The OCG is laid out without formal measurement; walls curve in plan but are also vertically out of plumb, to the extent they can present a danger to passersby. For safety and longevity, walls need to be laid using plumb lines. Arches over openings are sometimes too low, with excessive outward thrust. Adequately buttressed arches work well, but large cracks commonly appear where the surrounding structure cannot resist the thrust (see Fig. 6). Where arches have less lateral support in surrounding walls, a higher arch may eliminate cracking.

Another principal cause of cracking is differential settlement of soils beneath the heavy walls. There is speculation that leakage from canals or the Ain Al Faras (AAF) spring contribute to cracking and ultimately wall collapse. Photographs show however, that cracks were common a century ago at least, and that certain identifiable cracks have not increased since. Ordinary settlement, combined with no reinforcement, is a more likely cause. Walls are not positively attached to each other, causing cracks at wall junctions. Cracks also occur from weak adobe bricks, and no reinforcing agent, such as straw or coir, within the

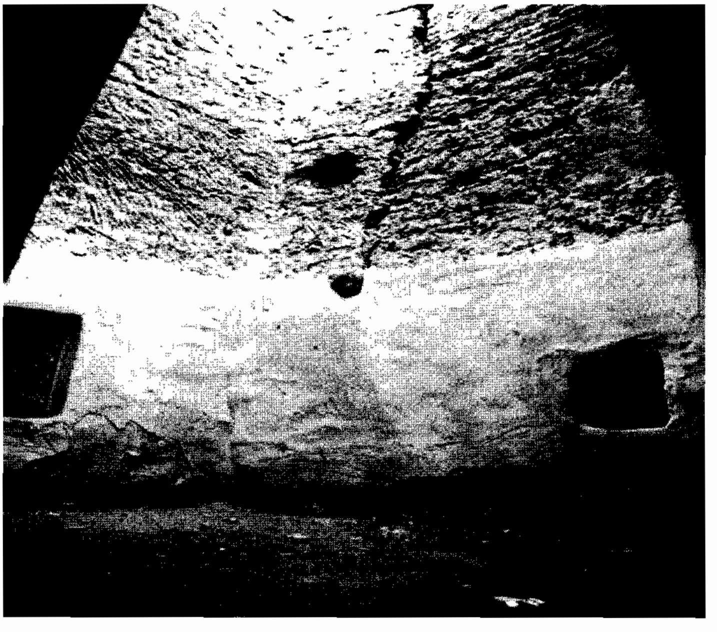


Figure 4: Settlement crack; loose *gyps* plaster below; sound dagga above

walls. Excavation to good-bearing soil and adequately wide stone foundations would reduce the chance of wall settlement. The use of coir or straw within the mix would increase adobe strength. Palm fronds laid in mortar-courses would provide a suitable material for positive connection between walls at corners and intersections. Steel reinforcing, foreign to the materials traditionally used, is unsuitable because its thermal expansion coefficient is very different from adobe.

Roof beams commonly pull out of their supporting walls when the beam sags badly, or when the wall moves outward, or the adobe fails beneath its load (see Section 3). A positive connection to the supporting wall could be achieved by laying stringers using a thin section of palm trunk within the appropriate mortar-course, and seating roof beams over it, with notches to prevent movement between beam and stringer. The stringer would also spread the roof beam loads, reducing damage from point loadings in the weak adobe walls.

2.3 Finishes

The local gypsum (*gyps*) plaster resists weathering but has significant shortcomings in practice. It is used as a protective wall capping, but actually accelerates the rate of erosion. The damage is hidden from view however, so remedial action is delayed. The process whereby hard *gyps* and cement plasters cause erosion is not well understood by the local craftsmen. Large areas of plaster commonly come away from the adobe substrate, on parapets in particular. In the past such damage would have been regularly repaired; plaster with several layers of repaired material is common. In all locations *gyps* plaster is poorly bonded with adobe substrate; even when entirely protected from rain, sun and wind, it consistently separates. It thus relies on mechanical keying to the parent wall at a relatively few locations. Where the *gyps* plaster is subject to additional forces, such as weathering or traffic, it cracks freely. The reliance on mechanical keying of the plaster to the adobe wall encourages craftsmen to continue building walls with large gaps in the mortar-course so the *gyps* plaster has a good key. Different thermal expansion rates cause the plaster to separate from the adobe substrate. With a high diurnal temperature range, daily movement between plaster and adobe causes internal abrasion. The dust produced (which is very evident), as well as ambient dust entering cracks, falls into the gap made between adobe and plaster, wedging the gap open further. Large separated sheets of plaster can be standing away from the adobe wall by up to 100mm. These act as gutters to trap rain against the wall, encouraging water entry into the adobe. Damage to the wall tops allows water into the whole building fabric, not just the parapets. The large exposed cavities also allow wind to bring sand and dust that scours out the softer adobe. Wall tops show severe coving behind and immediately below plastered areas, but lower down the same walls, where they have been finished with an adobe mortar (or dagga) plaster, the walls remain in good condition. Even where there is no added finish to adobe masonry, wall surfaces remain in good condition. The use of a dagga plaster more compatible with the adobe substrate would allow repairs to be longer-lasting. A lime wash would give the desired white colour safely. Lime plaster would be a suitable and readily available material when a tough plaster is needed; it would circumvent the high labour input of producing *gyps* plaster, and reduce the increasing, and deleterious, use of hard cement plaster.

2.4 Maintenance

An exodus from the OCG to New Ghadames (see Section 8) has meant a lack of maintenance due to lack of use, challenging the OCG's integrity. Regular re-plastering and other repairs are not undertaken in spite of serious visible decay. Private ownership makes it difficult for government agencies to take over maintenance of old houses. Many locals feel pride and spiritual connection in the old houses, but lack of money prevents many from effecting repairs, while lack of use removes the incentive.

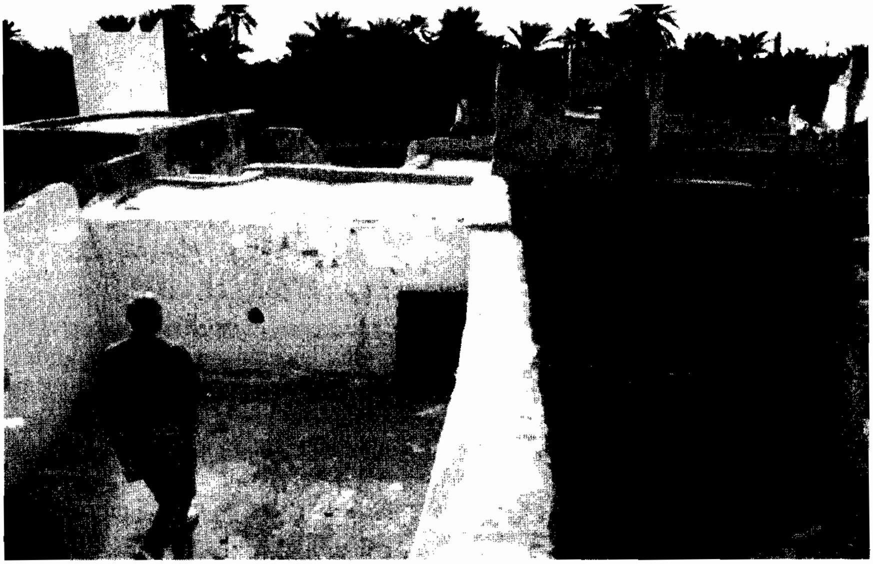


Figure 5: Roof terraces and parapets; damage and maintenance

The long-term solution is for the OCG to be re-inhabited, but several factors inhibit this. Interviews of Ghadamsi by the authors revealed some of the reasons the OCG is not re-inhabited. The new city is perceived as preferable because of its modern features, in spite of inferior thermal qualities. Lack of running water in OCG houses makes them less appealing, to the young in particular. Because plumbing in Libya is poor, with rust-prone un-galvanised steel pipes the norm, leaks are common; Ghadamsi are thus understandably suspicious of introducing plumbing into the adobe buildings. The OCG houses being ill-suited to modern appliances and furniture, and lack of vehicle access in the OCG, are further disincentives to return. The OCG disincentives could, however, be largely alleviated. Plumbing to good standards would present minimal risk of leakage and damage, while well chosen and sited appliances could suit OCG houses. Some vehicle streets have been accommodated in the OCG, and other carefully located access points could be added without adversely disturbing the city fabric. With careful attention in adapting OCG houses to modern practices, coupled with the growing housing shortage for young people, a new generation may be encouraged to re-inhabit the old city and begin the task of repair, reconstruction, and maintenance. Adapting to changing conditions, in this case modern lifestyles, is essential, as Diamond (2005) points out.

3 Resource Efficiency

The OCG houses form a single structural mass, sharing party walls between houses, although they are built at different times. There is no formal building code, or requirement to adhere to an orthogonal grid, or other town planning, apart from the traditions of the tribal and religious fabric. Houses progressing along a street are apt to stray increasingly from a straight line, giving the streets a pleasing meandering nature. Streets are built-over; the roof over the street is a floor of an upstairs store room, bedroom, or living room. Street roof height is defined by adjacent buildings, and may be just high enough to walk through without stooping.

Dimensions and design in the OCG are matched to available, but limited, natural materials. Materials are reduced by minimising all dimensions. Palm trunks are split to provide two roof beams, while arches span small openings. The similarly designed but unique houses are cubically built around a central room of about 5m. Ceiling heights are minimal, but each living room is double height, giving a sense of space to a compact building for a large family. Space is maximised throughout; narrow adobe steps lead to bedrooms and the roof terrace, with storage cupboards beneath. All spaces, but particularly the roof terraces are multi-functional. The roof terrace, enclosed on two or three sides, accommodates cooking (located so cooking smoke avoids lower rooms), dining and sleeping, being cool at night. Parapets provide wind shelter and privacy.

Flat roofs require minimum materials, and eliminate outward thrust from pitched roof members. Drain pipes projecting through parapet walls shed rain to the surrounding gardens or pedestrian spaces. Heavy rain brings all hands on deck, scooping up water to prevent the earth roofs from becoming sodden and overloading the palm trunk beams. The flat roofs often have insufficient slope from centre to outer edges, however; pooling rainwater leads to water ingress and increased weight, causing roof beams to fail. Pooling is sometimes 'solved' by adding more plaster to the centre to increase roof slope. This increases weight and leads to more overloaded roof beams. A primary cause of the problem is insufficient, or too widely spaced roof beams. Closer spaced or stronger roof beams, and a 'crown' shape on the finished roof surface would eliminate most of these problems. Resource efficiency is sustainable, but weak construction is unsustainable. This is particularly apparent in the construction of roofs.

4 Site

The existence and prosperity of Ghadames came from careful siting on and around AAF spring and resulting oasis. The site is on major historical caravan routes between southern Mediterranean and Atlantic ports, the African continent, and Mecca. Water, salt and food were traded for slaves, spices, ivory, cloth, leather, timber, and metals, which helped expand the range of available building materials. Date palm groves and gardens provided food and building materials.

Old Ghadames' architecture is site-specific, adapting to tough environmental demands: harsh sun; high day and low night temperatures; very low rainfall and humidity; scarce groundwater; scarce food; strong winds; sandstorms; marauder attacks; and limited available materials.

OCG is sited downwind from the oasis gardens, with many streets opening onto them. Evaporative cooling by the oasis tempers incoming air. The garden/building placement is no accident: falling topography would have allowed building placement either side of the spring. Careful siting relative to prevailing wind direction is part of the effective zero-energy climate control of Ghadames.

In contrast, New Ghadames ignores the environmental realities of the desert site (Chojnacki, 2003). Built in the 1970s and 1980s, it uses basic urban design: wide paved streets and concrete buildings, eschewing the technically and environmentally harmonious climate-oriented OCG urban scheme and design. It is only habitable with a substantial but unsustainable electrical supply, currently fossil fuelled.

5 Energy and Greenhouse Gases

Traditionally the energy sources used in Old Ghadames were firewood and passive solar energy. Firewood was used for cooking, making gypsum based plaster, and for firing pottery kilns. Other activities were done with muscle power, or relied on solar radiation.

Ghadames' urban and architectural design provides lighting, cooling, and excellent air quality in a completely passive manner. The built-over streets are labyrinthine, almost subterranean, reducing glare and heating from the desert sun.

Figure 6: Pedestrian street with light shafts and cracks

Along each street, just as light from a public square or other gateway reduces to darkness, light shafts are built from the rooftop to street level, providing just enough light to see by: walking proceeds from one pool of light to the next. The light shafts open to the outside, doubling as chimneys for warmed air, and drawing cool moist air from the gardens into the sand streets. This conditioned air is then drawn into the houses by stack effect. Houses have three main openings: the street entry door; the roof terrace exit; and the living room skylight. The solar-controlling skylights discharge internal air, drawing cooler ground level air via the entry door. Small windows may open to a light shaft or from a toilet or bedroom for additional light, but interiors are kept deliberately dim.

A combination of methods keeps the houses cool. Clustering the houses in one mass and stacking the rooms into a cubic form minimises exterior area exposed to the sun. White plaster reflects much solar radiation. Thick earth walls, roofs and floors provide huge thermal mass, averaging out high day and cool night temperatures, and providing several days relief from extremes. A minimum of openings prevents internal solar gain. Harsh light and extreme heat are thus dealt with in an entirely non-energy consuming, passively functioning, reliable way.

Without the OCG's climate-adaptive features the concrete buildings of New Ghadames are very hot. Chojnacki (2003) measured the average internal temperature of the new houses as 8.5°C higher than the OCG houses and 5.5°C *above* the ambient average, compared to 3°C *below* the ambient average for the old houses. The new houses are cooled with air-conditioning units, using fossil fuelled electricity from distant generation sources. Even so, the effectiveness of the OCG passive design, in spite of a lack of reticulated electricity for various uses, brings residents from the new to the old city daily.

Figure 7: New adobes for a garden wall

Building materials are all zero-energy and zero-emissions, except for the gyps plaster, used internally and externally that gives the beautiful white finish to the city. It is labour and energy intensive to make and requires burning with good quality palm wood before crushing and mixing. While attractive, the *gyps* plaster is not the most beneficial option for finishing the adobe surfaces. A simple earth-based dagga plaster, requiring no added energy, would be preferable. This would also make the Ghadames building materials entirely free of applied energy.

Low ambient humidity means adobe bricks dry in a day or two, eliminating the necessity to build stockpiles of adobes to construct a house. Moulding is done in small batches on the nearest flat ground, often a public square. Double-handling is reduced as adobes are shifted directly from the moulding area to the wall being constructed. All adobe mixing and construction is done by hand – no external energy sources are needed.

6 Benign Materials and Toxic Substances

The building materials available to Ghadamsi craftsmen were earth, water, rock, and date palm. The choice of adobe over stone construction, except for the foundations, is partly due to the labour of collecting and transporting rocks. Adobe allows much more flexibility in architectural form, and is more easily repaired. All materials are completely benign for users at all stages of the building lifecycle.

Date palm trunk is used for roof beams, doors, and shelves. Door lintels are made with a palm trunk beam and separate frame from palm trunk slab. Palm fronds are laid over the roof beams before stones and tamped soil are placed on top. The roof or upper floor is plaster finished. Palm fronds are used externally as temporary shading, farm fences, and a variety of other light-duty uses.

The natural materials of the OCG contain no substances directly toxic to human health. Nonetheless, a build-up of organic matter and salt in the soils can make them unsuitable for adobe making. The high salt content of the local water means soils gradually become too salty for growing crops, and must eventually be removed from farming areas. While this is a slow process, Ghadames' age illustrates the inevitable problems of contamination and the unsustainability of allowing systematic build-up of toxic substances. In Ghadames this is a manageable process to date. At a larger scale, toxic substance build-up is unsustainable. Organic matter in soil is largely a problem of poor waste disposal. Domestic refuse is allowed to mix with soil from demolished buildings. Since adobes are routinely recycled from demolition soil, the organic content in the subsequent adobes rises, compromising its quality and resilience.

7 Indoor Environment Quality

The conglomerate construction of the OCG gives minimum exposure to wind and sand storms. The skylight opening is easily covered to prevent ingress of material in a sandstorm, while the covered streets make the city habitable and navigable even during severe storms.

Adobe provides more effective thermal mass and is quicker to build with than stone or timber. It benefits air quality by regulating temperature and humidity, and absorbing smells (Alcorn, 1994). Local Ghadamsi, recognizing the inferior thermal properties of New Ghadames' buildings, believe the OCG is better because it is adobe, rather than because of the superior environmental design. Chojnacki (2003) observed an average external diurnal range in the OCG of 20°C (and a maximum of over 58°C), with no internal temperature change for weeks, along with internal humidity variation of zero, due to stable temperatures and high adsorptive capacity of the earth structure. Adobe is consequently slowly coming to be seen by residents as a superior material, having been viewed as a poor alternative to concrete buildings. The new buildings' thermal mass is actually similar to the adobe houses, but the lack of effective environmental design makes the new buildings unpleasantly hot. The heat of the new houses, ameliorated by air-conditioning, does not outweigh the perceived shortcomings of the old houses however, which are seen as embodying an old and inferior lifestyle. Ghadames' thermal environmental design is as perfect and sustainable as could be expected on its site. An appreciation of why the old city works so well has been lost since its design details were developed. Education about the science behind its functioning would assist in the re-habitation of the old city, and adoption of its building and design principles.

8 Water and Equity

Water from the appropriately revered AAF spring is carefully metered into specific canals with flow rates equitably adjusted to the needs of different farmers, clans and city regions. The modest water flow was always carefully managed, demanding social harmony, overseen by elders, to ensure its equitable distribution (Abufayed, Tumi, and Elgaud, 2004).

Water is channelled under the OCG buildings from the spring to the gardens, carrying waste and nutrients after it has supplied potable needs. The urban form is clustered around the spring, reducing canal length and evaporation.

In the 1970s the AAF water flow began reducing. Research reported by Moghadam (2000) suggests two likely possibilities: excessive local off-take, or aquifer water removals to coastal sites by large engineering projects; both of which represent unsustainable water resource management. Diminished flows from AAF exposed a limitation of the sanitary management of the OCG water system. The effect was a rise in disease, abandonment of the city, and construction of the unsustainable adjacent new city. Currently, Ghadames' water is predominantly pumped from local bores using external energy sources.

Old Ghadames' water system was well designed for use of the existing water resource, but not overuse. To return to a sustainable regime, water off-takes would need to reduce to natural flow limits, with total water use falling accordingly. This may mean cessation of gross removals to distant sites, and/or reduction of local water use for such things as modern flush toilets. The successful Old Ghadames tradition of dry 'composting' toilets would be an important step in reducing local water use. Return of the population to the OCG would achieve this.

The technical solutions achieved in OCG for water distribution are excellent, when followed. The authors found that leakage from AAF and the water canals has allowed rising damp into some nearby adobe walls, however. Capillary rise into the sensitive adobe is prevented with careful canal construction and rubble trench foundations with dry-stacked un-mortared stone foundations, *where budgets allow*. Walls with good stone foundations survive damp effectively, but where *poor* families built inadequate foundations, coving damage to walls occurs, and represents a significant threat to many buildings.

Rising damp appears as a construction or maintenance problem. Since technical solutions existed however, these do not provide a complete explanation. The origin of rising damp can properly be traced to financial and social inequity. Fundamentally, it is a small but important example of *intra*generational *inequality* compromising *inter*generational equality, as future users are forced to cope with the effects of poor construction. A degree of socioeconomic variation may be sustainable, but when this negatively impacts on the built environment, there are sustainability implications. A regulatory solution may be effective.

Abufayed, Tumi, and Elgaud (2004) reported repairs of the canals, reducing the primary cause of rising damp, but not solving the poor foundations problem, nor addressing the social, economic, or regulatory causes. Good traditional stone foundations above ground-level for future walls would ensure longevity. This known technical solution also requires regulatory and financial underpinning to ensure the social inequity cause is eliminated. In younger cities such intergenerational problems may not have had time to surface: Ghadames' age serves to illustrate problems that are only latent elsewhere.

9 Conclusion

Old Ghadames is a superb example of adobe architecture, adapted to the conditions of its site over millennia. It has been successful because it applies a full range of sustainability strategies. But it fails one particular sustainability test: adapting to new conditions. This failed sustainability test has lead to a series of cascading problems, each of which however, could be relatively simply overcome.

This paper has shown that the adaptations Ghadames needs to make are modest, and within the range of its existing materials, resources, and population.

Ghadames' historical sustainability was due, in particular, to it operating entirely within its own available energy and materials resources. The two most crucial resources were, and are, water and sunlight; one plentiful, one scarce. With a limited but reliable water resource, an extensive oasis was developed over millennia. The building mass of the OCG combines water, sun, and local soils into a building fabric which matched the specific requirements of the site.

Lighting, heating, cooling, and air conditioning – activities that take large amounts of energy in almost all cities – are achieved entirely passively, using only the sun and evaporative cooling from water and gardens, and the careful use of natural materials, to drive the processes.

If external factors had not impacted on Ghadames it would still be functioning in the same sustainable manner. But four particular problems have arisen that have not yet been adapted to. *Reduced water* flow and *changing lifestyles* have caused Ghadames to be evacuated. These have exposed a latent unsustainable characteristic: *weak adobe* construction and poor maintenance and protection methods. The reduced maintenance from lack of habitation only exacerbates these inherent weaknesses. The fourth problem has only just begun: increased severe *climate change rain events* demand robust adobe and maintenance going forward.

The sustainability features of Old Ghadames are threatened or lost without an ability to accommodate changed conditions. Without inhabitants Ghadames is a monument, not a sustainable city. To regain its sustainability, Ghadames needs to adapt to these changed and changing conditions. This means adapting to social change, including modern lifestyles, by incorporating appliances and running water into the old buildings, and by improving the resilience of the building fabric to withstand increased adverse weather, and uncertain maintenance. Moving into the 21st century, Ghadames can adopt refined building and use practices that raise performance and resilience. With adaptation, Ghadames can remain the Jewel of the Desert for millennia to come and be a prime example of sustainable practice whose fundamental lessons can be applied worldwide. Ghadames, past and present, shows not only that adaptation is essential for sustainability, but that even minor responses can make the difference between being sustainable and failing.

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