‘GREEN MAINTENANCE’: A SUSTAINABLE REPAIR APPROACH FOR HISTORIC MASONRY BUILDINGS

Brit Anak Kayan

University of Malaya
brit284@um.edu.my

ABSTRACT

The aim of this paper is to evaluate the efficiency of different stone masonry wall repair techniques and scenarios for historic masonry buildings in terms environmental sustainability, based on embodied carbon expenditure. Primarily, the objective of this paper is to gives insight on how ‘Green Maintenance’ concept and methodology associated with sustainable repair approach of historic masonry buildings, within ‘cradle-to-site’ boundary of life cycle assessment (LCA). The concept and methodology of ‘Green Maintenance’ were developed based on mathematical formulation to enable assessment of embodied carbon expenditure expended from different stone masonry wall repair techniques and scenarios for historic masonry buildings during maintenance phase. It is recognised that, ‘Green Maintenance’ plays an important roles in reducing embodied carbon expenditure, thus minimising the Environmental Maintenance Impact (EMI), typically associated with the deterioration and repair of stone masonry wall of historic masonry buildings. In the broader sense, the emergence of ‘Green Maintenance’ is not simply confined to historic masonry buildings and will be of use to those entrusted with the sustainable repair approach of other type of buildings, elements and components. This is parallel with increasing focus on the sustainable development.

Key words: Green Maintenance; sustainable repair approach; historic masonry buildings; life cycle assessment (LCA); mathematical formulation; Environmental Maintenance Impact (EMI), sustainable development
1.0 INTRODUCTION

1.1 Maintenance of historic masonry buildings: the current perspective

Hammond and Jones (2008a) state that the “UK construction industry consumes over 420 Mt of materials, 8 Mt of oil and releases over 29 Mt of carbon dioxide annually, including a significant quantity of new materials disposed of as waste”. In addition, UK’s construction sector significantly contributes for almost 47% of total CO₂ emissions with over 80% CO₂ emissions contributed by in-use (BIS, 2010). UKGBC (2013) expounded that, the construction and maintenance of buildings is responsible for around 50% of UK CO₂ emissions (UKGBC, 2013). Considering the large stock of existing buildings in the UK (see Maintain Our Heritage, 2004), a sizeable proportion of this embodied carbon expenditure (CO₂ emissions) is attributed to maintenance interventions and market in repair works in existing buildings (including historic masonry buildings).

Of the large and expanding market in repair works to the built environment, masonry contributes a significant cost. The Scottish Stone Liaison Group (UK) have estimated that the cost of masonry repairs required over a 20 year period as approximately £600 million (at 2010 prices) in Glasgow alone (SSLG, 2006). Comparatively, other major cities with a tradition of masonry construction in Scotland (such as Edinburgh) may also need similar levels of investment which benefits both local and international businesses. In addition to the cost perspective, this kind of investment not only provides significant advantage to the maintenance of the stone masonry walls of historic masonry buildings, but also can reduce the carbon expended in their repair. In 2007, the Scottish Building Standards Agency (SBSA) adopted a mechanism to evaluate the release of embodied carbon (CO₂ emissions) within maintenance in the ‘cradle-to-grave’ boundary of LCA (SBSA, 2007). Maintenance of historic masonry buildings should not only appreciated in the protection of their historic fabric and economic costs of existing built environment (through repair), but also essentially to be widely recognised on its ability to address an emerging concept and methodology of ‘Green Maintenance’.
1.2 ‘Green Maintenance’ for historic masonry buildings: an emerging concept and methodology

The Venn diagram in Figure 1 represents the traditionally accepted concept of sustainability with environmental, societal and economic factors, overlaid with the three factors that influence maintenance for historic buildings, namely; environment, cost and philosophy. Those maintenance interventions that intersect with all three contexts would potentially be considered as being the most ‘green’. The most ‘green’ maintenance intervention allows selection of maintenance options that provide a sustainable repair approach. To evaluate the long term maintenance requirements of historic masonry buildings in relation to the tripartite approach for ‘Green Maintenance’ concept and methodology, it is necessary to understand the cumulative effect of their routine maintenance operations not only in the terms of cost and philosophy, but also in the terms of environmental impact and sustainability.

![Venn diagram showing the intersection of environmental, societal, and economic factors with maintenance interventions for historic buildings.]

Figure 1: ‘Green Maintenance’ in sustainability context

1.3 ‘Green Maintenance’: a sustainable repair approach for historic masonry buildings

Figure 2 illustrates the typical approximate maximum life expectancy (longevity of repair) of different repair techniques for stone masonry walls. It reveals that different stone masonry wall repair techniques have different life expectancies.
and, therefore, contribute to different embodied carbon expenditure expended in repair.

Figure 2: Approximate life expectancy of stone masonry wall repair techniques

Note: See also http://www.maconline.org/tech/maintenance/point1/point1.html by Masonry Advisory Council (2014) for typical re-pointing life expectancy

Meanwhile, Figure 3 overlays the embodied carbon expenditure (CO$_2$ emission) for each maintenance intervention on the service condition graph. Each maintenance intervention (repair) is characterised by its longevity and embodied carbon expenditure. The figure distinguishes between ‘brown’ and ‘green’ maintenance: namely, those repairs of high and low carbon impact respectively. The cumulative effect of ‘brown’ maintenance increases the total embodied carbon expended far more quickly than ‘green’ maintenance. Conversely, the former is synonymous with less efficient repairs, which have lower longevity and higher embodied carbon (more CO$_2$ emission) compared to the latter.
Figure 3: Relationship between longevity of repair and embodied carbon expenditure

Figure 4 shows how the embodied carbon expenditure expended in building’s fabric. It assumes that all repairs are immediately replaced once their life expectancy (longevity of repair) has been reached. In the case of historic masonry buildings, this is the cumulative effect of maintenance interventions over the stone masonry walls’ life, denoted by n1, n2 and n3. Each intervention (repair) has embodied carbon expenditure (ce) and a longevity of repair (l). The total embodied carbon expended by maintenance interventions through repair is illustrated by Equation No. (1).

Figure 4: Determination of theoretical embodied carbon expenditure in building’s fabric
Carbon expenditure on maintenance \(= \sum_{i=1}^{n} ce_i \)

Equation No. (1)

where:

\( n \) = number of interventions \\
\( ce_i \) = embodied carbon expenditure for the \( i \)th maintenance intervention [evaluated by within ‘cradle-to-site’ tools of LCA] [kgCO\(_2\)/kg/m\(^2\)]

Maintenance of buildings is crucial in ensuring that the financial, economy and societal capital invested in their construction is holistically expended. Increasingly, the emergence of ‘Green Maintenance’ becomes a shift of paradigm relating to sustainable repair. This paper envisaged the development of mathematical formulation of life cycle assessment (LCA) approach of ‘Green Maintenance’ for sustainable historic masonry buildings repair within ‘cradle-to-site’ boundary during maintenance phase, focusing on the following aims and objectives.

2.0 OBJECTIVES

This paper attempts to ascertain answers to the following specific objectives:

a) To review maintenance of historic masonry buildings from the current perspective with an insight on emerging concept, methodology and sustainable repair approach of ‘Green Maintenance’;

b) To evaluate the efficiency of different techniques and scenarios of stone masonry wall repair techniques for historic masonry buildings based upon how ‘green’ they are based on embodied carbon expenditure within ‘cradle-to-site’ of LCA; and

c) To develop and test sustainable repair approach of ‘Green Maintenance’ based on generated EMI expended in stone masonry wall repairs for historic masonry buildings.
3.0 METHODOLOGY

The evaluations were made within the ‘cradle-to-site’ of Life Cycle Assessment (LCA) and the selected maintenance period. Using a set of unit processes and workflows from each repair technique, calculation procedures were undertaken in different stages, mainly during the maintenance phase of historic masonry buildings (Figure 5).

![Figure 5: Process map of the life cycle of stone for historic buildings](Source: Kayan, 2013.)

3.1 Functional units and cumulative embodied carbon expenditure for repair

Initially, embodied carbon expenditure to repair 1m\(^2\) wall for each stone masonry wall repair technique (functional units of kgCO\(_2\)e/kg/m\(^2\)) were determined based on maintenance intervention (n) and total repaired area of stone masonry wall
(m²), within the ‘cradle-to-site’ of LCA on yearly basis, for the selected maintenance period. Cumulatively, the embodied carbon expended for each repair technique was then calculated by multiplying the total area of wall repaired (m²) with their respective generated functional units. Overall total of embodied carbon expenditure for all undertaken repair techniques for stone masonry wall within ‘cradle-to-site’ could be calculated using Equation No. (2):

Total approximate of embodied carbon expenditure (per 1 m² stone masonry wall repaired)

\[ \sum ECE_{cradle-to-site} (m^2)_n = ECE_{cradle} - to - gate (m^2)_n \]

\[ + ECE_{gate} - to - site (m^2)_n \]

Equation No. (2)

where;

- \( ECE_{cradle-to-gate} (m^2)_n \) = embodied carbon expenditure value on every 1m² of repaired stone masonry wall using relevant repair techniques within ‘cradle-to-gate’ boundary
- \( ECE_{gate-to-site} (m^3)_n \) = embodied carbon expenditure value for transporting repair materials used in repairing 1m² stone masonry wall using relevant repair techniques within ‘gate-to-site’ boundary

The ‘Green Maintenance’ results were then tested on its EMI, by evaluating the influences of longevity of repair within the selected maintenance period. The testing is to ascertain ‘Green Maintenance’ practicality and compatibility, either for single or a combination of stone masonry wall repair techniques in different repair scenarios.

### 3.2 Repair techniques and scenarios

In this paper, four repair techniques and scenarios were compared based on their EMI, including natural stone replacement, pinning and consolidation followed by replacement, repeated plastic repair and single plastic repair followed by stone replacement. They are diagrammatically represented in Figure 6. Comparatively, details of different repair techniques and scenarios compared are explained as follows:
Figure 6: Repair techniques and scenarios for stone masonry wall


a) Scenario 1: Replacement

Natural stone replacement was assumed to require the cutting back or indenting of approximately 100mm (0.1m) or 0.10m$^3$ of volume (1m x 1m x 0.1m = 0.10m$^3$) of the defective material in natural stone. This was then followed by building in a new section of stone with the approximate dimension of 1m x 1m x 0.1m of respective length (L) x height (H) x width (W). For this paper, the life expectancy of this repair option was taken to be hundred years (only one intervention in a hundred years period).

b) Scenario 2: Repeated repointing

Repeated repointing is common in repairing loose, open, soft, crumbling or washed out bedding and jointing mortar in stone masonry walls. For this repair scenario, lime-based mortar was encouraged as it lets the wall breathe. The decayed mortar from the face of the stone masonry wall can then be cut by raking out to reach the good mortar that remains deep in the wall (two or three times the thickness of the original mortar joints on the surface of the wall). The repair depth should be cleaned out to a minimum depth of 25mm (38–50mm for wide joints, such as those in a rubble
wall, if necessary). Repeated repointing intervention is commonly reapplied every twenty-five years (five times of intervention in a hundred years period).

c) Scenario 3: Pinning and consolidation, followed by stone replacement

In general, pinning and consolidation scenarios for the stone masonry wall were assumed to require high-grade threaded stainless steel dowels, which should ensure the survival of the historic fabric of the stone masonry wall for an initial twenty-year period. In the case of this paper, high-grade threaded stainless steel dowels (grade 304), as specified by Institute of Stainless Steel Forum (ISSF), that were 100mm long and 6mm diameter, were used and inserted at an approximate minimum of 100mm spacing or one hundred pieces in 1m² stone masonry wall with an average weight of 46g per piece (http://www.valbruna.co.uk/products/revol/dowel-bar-details) (Valbruna, 2014a) and tied up together with stainless steel tying wire (http://www.valbruna.co.uk/products/revol/tying-wire-details) (Valbruna, 2014b). After a twenty-year period the repair may fail and require further intervention in the form of replacement of stone. As previously mentioned, this process requires the ‘cutting out’ of the defective masonry to a depth of approximately 100mm (0.1m³) and the building in of a new section of stone. The replacement stone will last beyond the hundred years and so only 0.8 of its EMI was attributed to the selected arbitrary periods.

d) Scenario 4: repeated plastic repair

Under the repeated plastic repair scenario, the decayed surface of the stone masonry wall was assumed to be cut back to a point at which a sound substrate was reached and lime-based mortar was used to resurface the stone. The resurfacing of the stone used lime-based mortar (with aggregates) materials for a 1m² masonry wall plastic repair with a minimum of 3–12mm depth (depending upon the thickness of the joints) of undercut or cutback, with approximately 9mm thick layers (base coats) and 6mm finishes. Meanwhile, a minimum depth of 40mm were undercut or cutback with an approximately 9mm thick layer (base coats) and 4mm finish (http://www.lime-mortars.co.uk/calculators/plaster) for multi-layer patch. Commonly, the intervention was reapplied every thirty years (3.33 times in the 100 years period).
e) Scenario 5: single plastic repair followed by stone replacement

In contrast to scenario four, if deterioration had occurred to the substrate forming the base of the plastic repair, it is necessary to cut back the natural stone further. This prevented repeated plastic repairs due to the build-up of excessive thickness. In this scenario, the plastic repair and the decayed natural stone is assumed to be removed after thirty years and new stone built in to a depth of 100mm. As with scenario three, the replacement stone will last beyond the hundred years. Therefore, only 0.7 of its EMI was attributed to the specified period. An estimated longevity of repair for stone masonry wall repairs techniques was based on life expectancy data. Within selected maintenance profiles of one hundred years, the number of maintenance interventions (n) will be a function of life expectancy of each selected repair technique (BGS, 2008).

3.3 Total Environmental Maintenance Impact (EMI)

‘Green Maintenance’ model results were generated by evaluating the influences of longevity of repair within the selected maintenance period (in this case is within a hundred years period). This could be expressed as in Equation No. (3):

\[
\text{Total of Environmental Maintenance Impact (EMI) (100 years)}
= \sum_{n=1}^{N} EMI(100\text{yrs})_{\text{cradle-to-site}_{tn}} = EMI_{\text{cradle-to-site}_{t1}} \\
+ EMI_{\text{cradle-to-site}_{t2}} ... EMI_{\text{cradle-to-site}_{tn}}
\]

Equation No. (3)

where;

\( n \) = either single or a combination of repair techniques in different repair scenarios or techniques \( t_n \) for one hundred years of maintenance profile periods

\( EMI_{(100\text{yrs})_{\text{cradle-to-site}_{tn}}} \) = total embodied carbon expenditure for quarrying/mining, processing and manufacturing and transporting of repair materials used in repairing stone masonry walls of historic masonry, using either single or a combination of repair techniques in different repair scenarios within one hundred years of maintenance profile periods within the ‘cradle-to-site’ boundary [generated from Equation No. (2)].
### RESULTS AND DISCUSSIONS

Table 1: Embodied carbon expenditure associated with alternative repair scenarios

<table>
<thead>
<tr>
<th>Stone replacement</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Plastic repair, then stone replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stone</td>
<td>Repointing</td>
<td>Pinning, consolidation, then</td>
<td>Plastic repair</td>
<td>Plastic repair, then stone replacement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Indenting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ lime grout mix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kgCO₂e/m²</td>
<td>24.683</td>
<td>-</td>
<td>24.683</td>
<td>-</td>
<td>24.683</td>
<td></td>
</tr>
<tr>
<td>Number of</td>
<td>1</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>interventions (n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total EMI</td>
<td>24.683</td>
<td>19.746</td>
<td>17.278</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Indenting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ dowels + lime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kgCO₂e/m²</td>
<td>54.481</td>
<td>-</td>
<td>54.481</td>
<td>-</td>
<td>54.481</td>
<td></td>
</tr>
<tr>
<td>Number of</td>
<td>1</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>interventions (n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total EMI</td>
<td>54.481</td>
<td>43.585</td>
<td>38.137</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) Dowels + epoxy resin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kgCO₂e/m²</td>
<td>70.730</td>
<td>-</td>
<td>70.730</td>
<td>-</td>
<td>70.730</td>
<td></td>
</tr>
<tr>
<td>Number of</td>
<td>1</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>interventions (n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total EMI</td>
<td>70.730</td>
<td>56.584</td>
<td>49.511</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Repointing

Lime mortar pointing

kgCO₂e/m² - 1.641 - - -

Number of interventions (n) - 4 - - -

Total EMI - 6.564 - - -

Pinning and consolidation

(a) Dowels + lime grout mix

kgCO₂e/m² - - 29.402 -

Number of interventions (n) - - 1 -
<table>
<thead>
<tr>
<th></th>
<th>Total EMI</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(b) Dowels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ epoxy resin</td>
<td>kgCO₂e/m²</td>
<td>-</td>
<td>-</td>
<td>29.402</td>
<td>-</td>
</tr>
<tr>
<td>Number of interventions (n)</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total EMI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>46.047</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Plastic repair           |           |       |       |       |       |
| **(a) Lime-based mortar + aggregates** | kgCO₂e/m² | - | - | 6.489 | 6.489 |
| Number of interventions (n) | - | 3.33 | 1 |
| **Total EMI**            |           |       | 21.608|       | 6.489 |
| **(b) Lime-based mortar multi-layer plastic repair** | kgCO₂e/m² | - | - | 113.60 | 113.608 |
| Number of interventions (n) | - | 3.33 | 1 |
| **Total EMI**            |           |       | 378.31| 6.564 | 113.608 |

| Overall Total EMI        |           | 149.494| 6.564 | 195.364| 399.92 | 225.023 |

Source: Kayan, 2013

**Note:**
Materials data in Table 1 are also derived from Crishna et al., (2011) and Hammond and Jones, (2008a, 2008b, 2011 and 2014); transport data are derived from the Department of Environment and Rural Affairs (DEFRA) and Department of Energy and Climate Change (DECC) (2009) and the Institute for Energy and Environmental Research (IFEU) (2008). Embodied carbon expenditure for materials transportation (gate-to-site) @ 132 gm CO₂ emission factors per tonne km or 1.32 x 10⁻⁴ kgCO₂ per kg km emission factors using updated 2008 CO₂ emission factors per tonne km for all HGV road freight (based on UK average vehicle loads in 2005) (IFEU, 2008; Defra/DECC, 2009) or mass (kg) * emission factors per kg km * distance (km); sample taken from historic masonry buildings of 22-30, Shandwick Place of Edinburgh, Scotland.
Table 1 summarises the EMI [generated from Equation No. (3)], evaluated in terms of embodied carbon expenditure, over the 100-year maintenance period for different repair techniques and scenarios at the same sample properties (in this case is 22-30, Shandwick Place of Edinburgh). The results show that there are high functional units (kgCO$_2$/kg/m$^2$) in making repairs using the natural stone replacement technique. Within a 100-year maintenance profile period, however, only one intervention is undertaken with this technique, compared to three, four and five interventions for plastic repairs, repointing and pinning and consolidation, respectively. This is due to the natural stone replacement technique having the longest longevity of repairs within the same period. It can be concluded that the higher the longevity of repair (the fewer interventions undertaken) using the selected repair techniques, the less carbon expended on repairs (less CO$_2$ emissions). This is parallel with sustainable repair approach of ‘Green Maintenance’ concept and methodology.

5.0 CONCLUSIONS

This paper successfully demonstrated that ‘Green Maintenance’ has shown its capability in evaluating EMI of different repair techniques and scenarios in repairing stone masonry walls of historic masonry buildings, based on LCA. ‘Green Maintenance’ will be positively welcomed as our society moves towards low carbon economy and materials and ‘green’ procurement. As low carbon trading in building industry becomes more prevalent, the sustainable repair approach of ‘Green Maintenance’ can be converted into a supplementary in maintenance decision making process by substantiating the philosophical defensibility and sustainability of maintenance and repair. In addition, this approach also able to achieved more rigorous analysis of the disparity between philosophy and cost versus embodied carbon expenditure i.e. CO$_2$ emissions from repair. Significantly, sustainable repair approach of ‘Green Maintenance’ is parallel with increasing focus on the sustainable development and universal in its nature.
ACKNOWLEDGEMENTS

The author would like to thank Dr. Alan M. Forster (Tenured Assistant Professor) and Professor Philip F.G. Banfill of School of Energy, Geoscience, Infrastructure & Society, Heriot-Watt University, Edinburgh, Scotland, United Kingdom for their valuable inputs throughout the completion of this paper.

REFERENCES


