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Viability and performance of demountable composite connectors

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ABSTRACT

Material production, and associated carbon emissions, could be reduced by reusing products instead of landfilling or recycling them. Steel beams are well suited to reuse, but are almost impossible to reuse when connected compositely to concrete slabs using welded studs. A demountable connection would allow composite performance but also enable reuse of both components at end-of-life. A recent conference paper proposed a demountable connection using machined studs, whose performance is explored using standard push-off tests. However an alternative concept, presented for the first time in this paper, uses M20 bolts as composite connectors, connecting the slab to the beam through holes in the beam flange and securing with nuts. Two composite beams, one of 2m span, the other of 10m span, are constructed and laboratory tested in three- and six-point bending respectively. Both are service loaded, demounted, reassembled and tested to failure. The results show that both have a strength similar to that predicted from calculation using Eurocode 4, and the longer specimen has similar performance to a comparable welded-connector composite beam. This suggests that such composite beams can be successfully demounted and safely used, thus enabling reuse and therefore reducing carbon emissions.

1. INTRODUCTION: THE OPPORTUNITY TO REDUCE CARBON EMISSIONS BY REUSING COMPOSITE STRUCTURES

Every year 1,500 million tonnes of steel are produced worldwide (World Steel Association, 2010). Although steel production processes are relatively efficient (Allwood et al., 2012), large amounts of energy are still required, which cause the emission of carbon dioxide into the atmosphere – approximately 9% of anthropogenic global emissions from energy and processes (International Energy Agency, 2008). The construction industry uses approximately half of steel produced (Wang et al., 2007) and reuse has been identified as having potential to reduce this tonnage, and hence associated carbon emissions (Allwood et al., 2012).

Addis (2006) identifies three characteristics a component must have to be reuseable: it is not worn, yielded or corroded; it is not a superseded technology; it can still interface with new components. Structural steel beams meet these requirements provided they have not been exposed to fire, seismic or other extreme scenarios as their standard sizes and connection technologies have not changed in the past 50 years (Addis, 2006); thus they are ideal candidates for reuse. If the rate of reuse can be increased from the 1.5% of steel beams exiting construction currently (Kay & Essex, 2009) then there is potential to decrease demand for new and recycled steel.

Composite floors are the most common construction system for multi-storey buildings in the UK, accounting for approximately 40% of such floor area built annually (BCSA, 2011). However composite construction is listed as a barrier to deconstruction (Densley Tingley & Davison, 2006) with Webster & Costello (2005) recommending it be avoided in designs for deconstruction. If a system can be found that permits composite action and also allows deconstruction, then reuse can be enabled and hence carbon dioxide emissions reduced.

2. REVIEW OF PUBLISHED LITERATURE

Research into behaviour and prediction of composite construction has used „push tests' extensively to verify models and formulae; however push tests have recently been shown to have poor correlation with actual construction practice. All papers to date, with one exception, have examined welded connectors.

2.1 Review of literature on traditional, welded-connector composite beams

Engineering understanding of composite steel-concrete construction systems has evolved over the past century mainly based on „push tests' supplemented by modelling. Recent research suggests that these tests do not correlate well with beam tests, which are more reflective of the actual use of composite beams. Design guidance has been continually updated to incorporate developments in understanding and research.

Hicks (2007) explains that „push test specimens' (shown in figure 1) were developed in the 1930s to determine the behaviour of composite connectors (called „studs') and the standard test has changed little since. All published literature uses results from push tests (either new or previously published) to validate theoretical models and to appraise and update design guidance. For instance, Hawkins & Mitchell (1984) conclude that connector spacing and geometry greatly impact the failure load, while Qureshi & Lam (2012) verify their finite element computer models against push tests. That design codes BS 5950-3.1:1990 and BS EN 1994-1-1:2004 only provide guidance for welded connectors is evidence of the ubiquity of this form of composite construction in buildings.

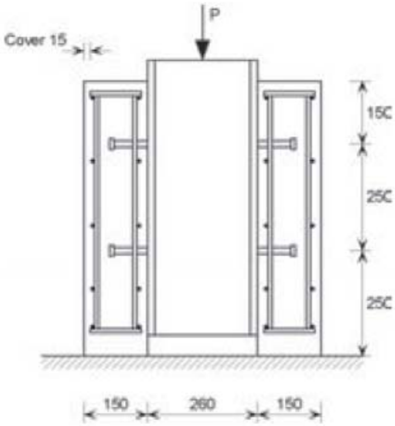


Figure 1: Push test specimen for profiled decking, taken from Hicks (2007). Load P is applied at the top end of the steel section to determine the load-slip behaviour of studs.

Patrick (2004) identifies 11 failure modes for composite beams and further claims that design codes for trapezoidally-profiled decking considerably underestimate strengths and slip capacities for welded connectors. Hicks (2007) responds to Patrick's claims, performing 6 push tests and 2 beam-bending tests, showing that the two sets of results have poor correlation. Given composite floors in buildings are subject to loading in bending, Hicks concludes that the beam tests are more reflective of the real behaviour of such construction, and hence that design specifications are still safe (though a few minor corrections are needed).

2.2 Review of literature on demountable connector

Only one academic reference to demountable connectors was found; in a conference paper, Lam & Saveri (2012) describe experiments using connectors machined from traditional studs with threads (shown in figure 2) so they can be bolted onto a beam and disassembled. These experiments show that the bolted connection performs suitably in a push test, but beam tests were not completed.

Figure 2: Demountable connectors machined from traditional studs, taken from Lam & Saveri (2012)

2.3 Findings from literature review

In the body of published work on composite steel-concrete construction there has been a large number of push tests but few beam tests – despite poor correlation between the two and beam tests being closer to actual use of connectors in construction. None of the research into connector failure modes, for example Yuan & Johnson (1998)'s theoretical failure models, inherently precludes bolt use as none require moment resistance at the connector base. To date there is only one article examining demountable connectors, and none which presents results from beam tests on demountable connectors, or on tests using bolts as connectors. This research, therefore, investigates the behaviour of steel bolts used as composite connectors in two beam tests.

3. METHODOLOGY TO TEST A DEMOUNTABLE CONNECTOR DESIGN

Two beam tests are undertaken in the laboratory to investigate the behaviour of steel bolts as demountable composite connectors. Both specimens are tested under bending and results compared with predictions from calculation. The results from one specimen are additionally compared with previously published results of similar beam tests with welded studs.

3.1 Laboratory testing of demountable connector design

Two composite beam specimens were constructed and tested in the laboratory: one 2m in length and one 10m in length. A commercially available profiled deck (Multideck 60-V2) was laid on top of the beam and connected to it by M20 bolts through 24mm holes pre-drilled through the decking and top flanges of the beam, fastened by washers and nuts (tightened to 100Nm) on either side as shown in figure 3. Displacement sensors were fitted to the lower nuts, the loading points and third points along the beam in both specimens; additionally strain gauges were attached at 15 cross-sections along the longer specimen. All sensors were calibrated to within 2% accuracy. C16/20 concrete was poured to form a 140mm thick slab, 0.5m wide in the 2m specimen and 2.5m wide in the longer specimen. Cube and tensile tests were performed to obtain the materials' properties.

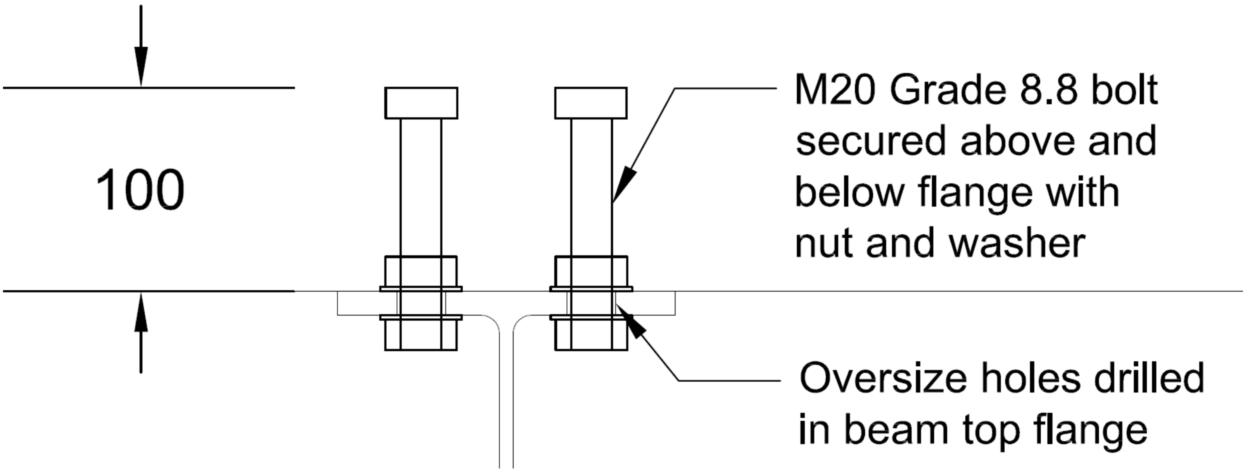
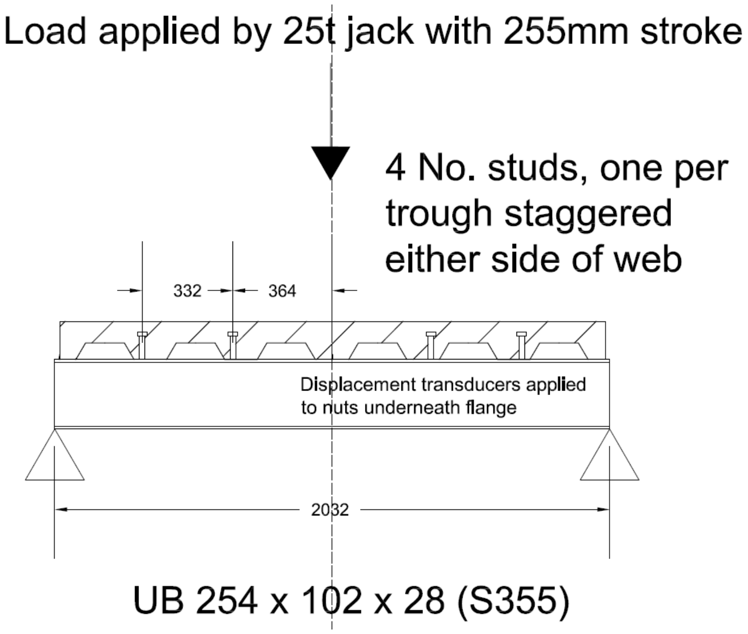
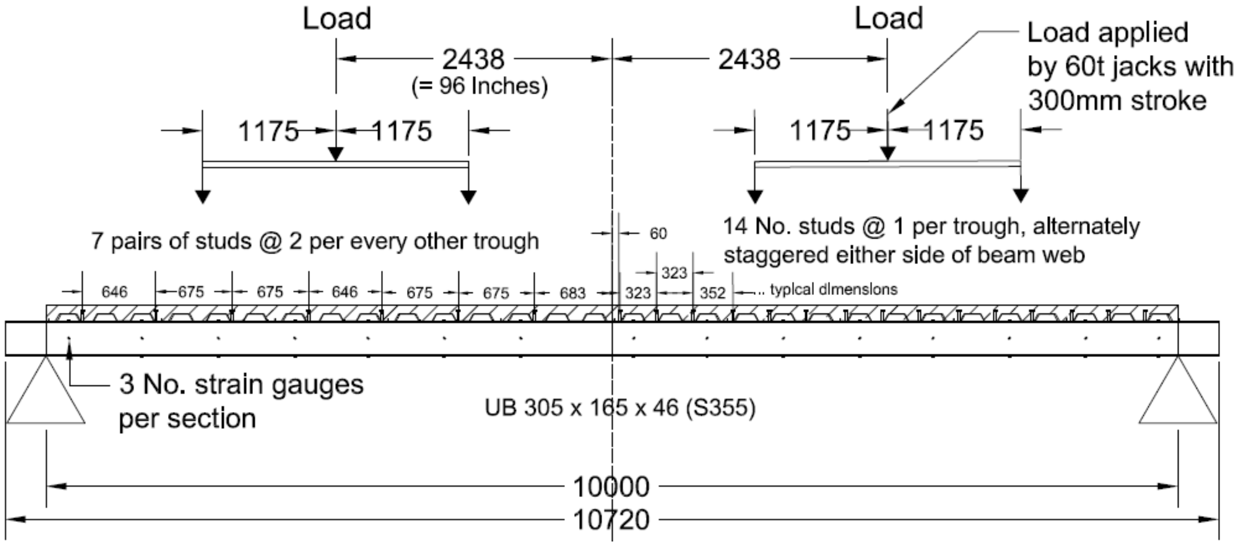


Figure 3: Section through a pair of demountable connectors

Both beams were loaded in the laboratory using hydraulic jacks mounted on rigs. The shorter was tested under 3-point bending, the latter under 6-point bending, at points show in figure 4. The beams were initially loaded to a service load equivalent to 6.5kN/m^2, determined from typical office loading specified by Eurocode 1, unloaded and demounted – the bottom nuts released and the beam lowered clear of the slab (which was separately supported for this process). The beams were then reattached and reloaded until failure.



a) 2m specimen



b) 10m specimen

Figure 4: Geometry and loading setup for the two tested specimens

3.2 Analysis of results and verification

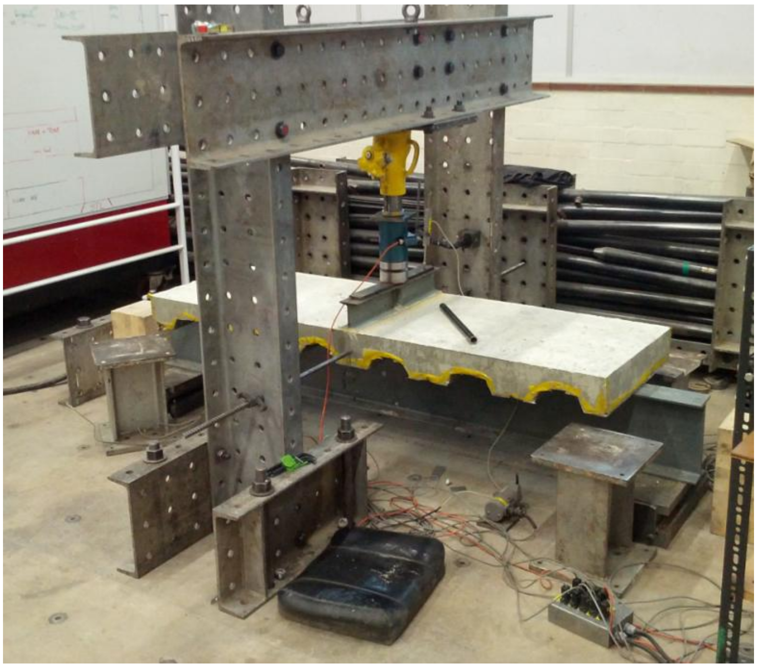
Data were recorded from the displacement and strain gauges along the specimens, and from a loadcell attached to each jack. These were analysed to output moment-displacement curves for the beams and for each connector. These were compared with calculations done to Eurocode 4-1-1 and also to an analysis from first principles. The results for the larger specimen were compared with Hicks' (2007) previously published results for a beam of identical geometry, composition and loading, but using welded studs instead of bolted, completed in the same laboratory in 2005.

4. RESULTS FROM DEMOUNTABLE CONNECTOR TESTS

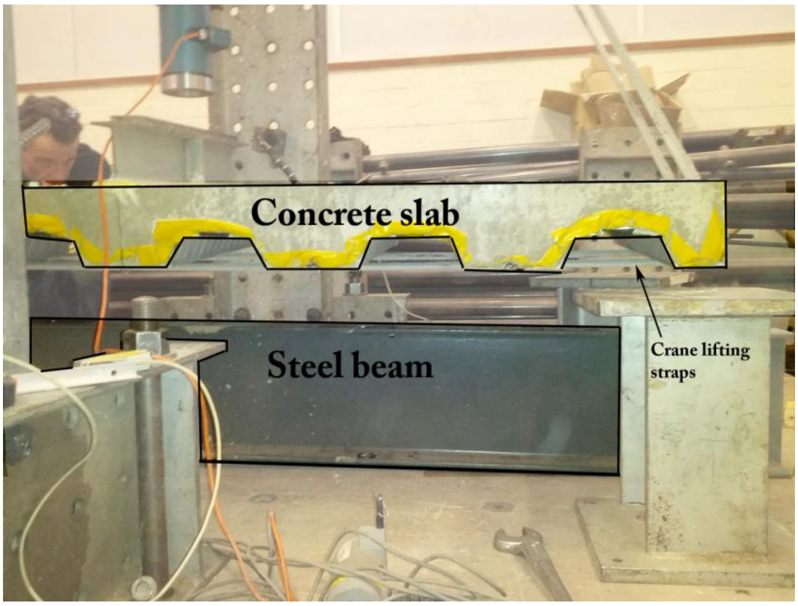
Results are presented for the two beam specimens tested, showing agreement within 10% of predicted values. Additionally both specimens were successfully demounted, proving the concept is achievable in practice. The results of the latter beam test are compared with those previously published from a related experiment and found to agree within 20%.

4.1 2m specimen results

The 2m specimen was successfully loaded to service, demounted and reassembled. Figure 5 shows the assembled beam and then the demounted beam below the suspended slab. It proceeded to fail at a jack load of 485kN, which caused a moment of 246kNm. Although a plastic hinge had started to form in the steel and the moment had started to plateau, the final failure was caused by shear in the concrete at the loading point. All bolts displaced no more than 2mm, less than the 6mm limit specified in Eurocode 4-1-1.



a) initial, assembled 2m specimen and loading rig



b) demounted beam (background faded to highlight separated steel and concrete)

Figure 5: 2m specimen before and after demounting

Results from the material tests are given in table 1. Completing calculations to Eurocode 4-1-1 with these values gives a predicted failure moment of 234kNm, which is within 5% of the experimental value. Analysis of strains from first principles predicts failure at 248kNm, which is within 1% of the experimental value.

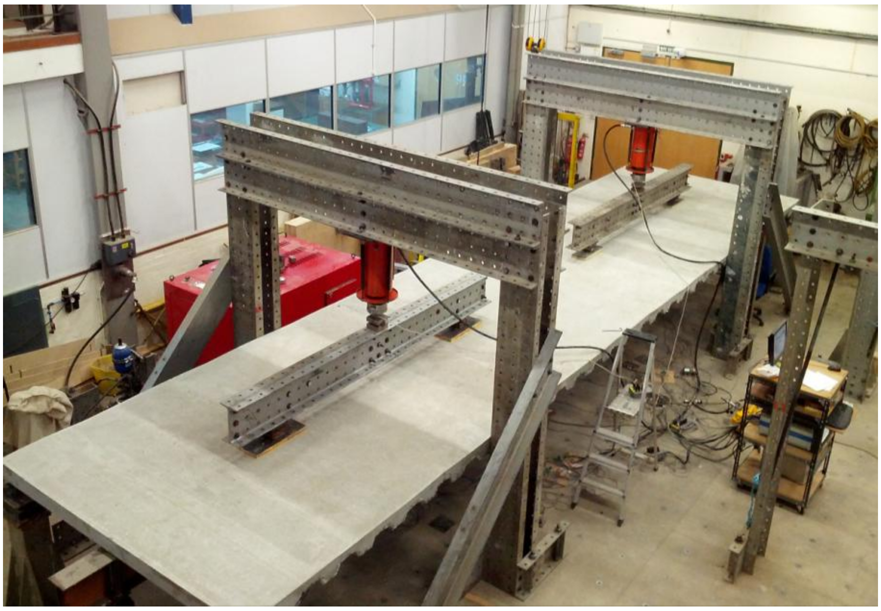
Table 1: Measured material properties for 2m specimen

UB 254x102x28 S355 steel beam	
Mean flange yield strength (f_{ym})	420 MPa
Mean web yield strength (f_{ym})	480 MPa
C16/20 concrete	
Age	14 days
Mean compressive cube strength ($f_{cm, cube}$)	21.14 MPa
Characteristic compressive cube strength($f_{ck, cube}$)	20.6 MPa
Characteristic compressive strength (f_{ck})	16.5 MPa*

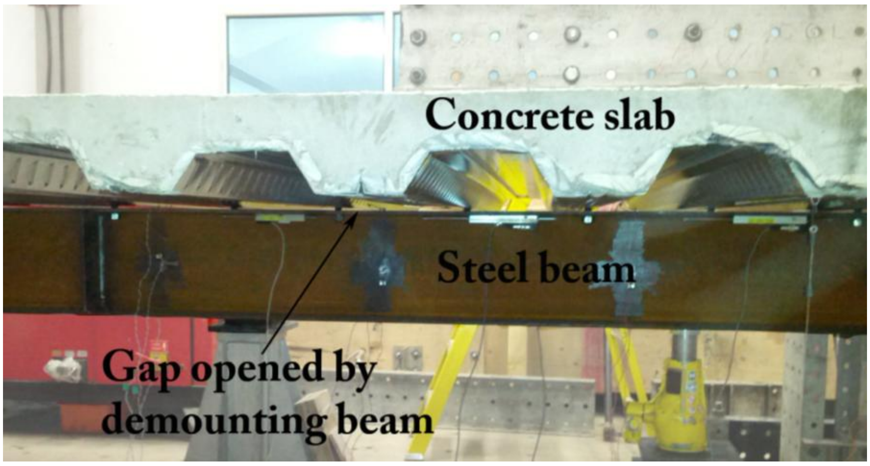
*Calculated from BS EN 1992-1-1 Section 3

4.2 10m specimen results

The 10m specimen was successfully loaded to service, demounted and reassembled; the latter two processes were achieved quicker and with less forcing than had been anticipated. Figure 6 shows the test specimen in initial and disassembled states. The reassembled beam was then loaded until the deck started to delaminate from the slab in the portion of the beam with pairs of studs. First yield occurred at load in each jack of 105kN, which caused a moment of 351kNm. No bolt slipped more than 2mm.



a) Initial, assembled 10m specimen with test rigs



b) nuts loosened and beam lowered below slab intact
(background faded to aid comprehension)

Figure 6: 10m specimen before and after demounting

The results of the cube and coupon tests are given in table 2. Completing calculations to Eurocode 4-1-1 with these values gives a predicted failure moment of 388kNm, which is within 11% of the experimental value. Analysis from first principles predicted a failure moment of 356kNm, which is 2% higher than the experimental value.

Table 2: Material properties for 10m specimen

UB 305x165x46 S355 steel beam	
Mean flange yield strength (f_{ym})	364 MPa
Mean web yield strength (f_{ym})	407 MPa

C16/20 concrete	
Age	18 days
Mean compressive cube strength ($f_{cm, cube}$)	13.75 MPa
Characteristic compressive cube strength($f_{ck, cube}$)	13.33 MPa
Characteristic compressive strength (f_{ck})	10.66 MPa*

*Calculated from BS EN 1992-1-1 Section 3

4.3 Comparison with previously published results

Table 3 shows the 10m specimen results alongside those from Hicks (2007), from whose drawings and details this specimen was constructed. Hicks' experiment had a characteristic concrete strength of 12.4MPa at testing which may explain his higher value for plastic moment – particularly as failure occurred in the slab. The concrete for the demountable experiment was only 70% of its expected strength, despite being provided by a commercial supplier, which prevented a like-for-like comparison. It is unclear why Hicks' deflection value is also higher.

Table 3: results from 10m specimen compared with those from Hicks (2007)

Result	10m specimen	Hicks (2007)	Difference
First yield moment (kNm)	351	375	7%
Midspan deflection at first yield moment (mm)	161	190	18%

5. DISCUSSION OF IMPLICATIONS OF RESULTS

The experimental results demonstrate that a composite beam with demountable studs performs in a similar manner to such beams with welded studs, predictably meeting the required safety standards. However further innovations would be required to allow demountable connectors to be used on commercial sites – these are explored, finding two challenges and two potential solutions. Policy recommendations are made to encourage adaptation of demountable and reuseable systems in construction.

5.1 Implementation of demountable composite beams in industry

The proposed, demountable connector system can be implemented on a construction site; however there certainly will be a cost penalty as compared with welded studs for two reasons: the material cost of bolts is approximately three times higher than that of welded studs, and additional labour is required to install bolts, as one person must be (at height) holding the nut underneath the decking whilst another is tightening it from above.

Further research can address the first of these issues – Lam & Saveri (2012) machined a traditional stud into a demountable version, so it is likely that a demountable, cost-efficient (when mass produced) solution can be found. Increased use of prefabrication and „smart' construction technology can address the second issue – the concrete slab could be manufactured off-site with the bolts cast in desired locations protruding from the soffit, and then transported to site (a leading UK construction firm already prefabricates concrete units for use on site, giving a programme and cost savings). The steel beam can be predrilled with holes for the bolts as part of the automated fabrication process so that the slab fits neatly on top, requiring only one person to tighten the nuts from below.

5.2 Policy recommendations

There are at least two policies that could be implemented to encourage reuse in construction through building demountable structures: a deposit scheme and a leasing business model.

Firstly authorities could require a deposit to be paid on construction of a new structure and increasing proportions of it returned at end-of-life depending on how high up the waste hierarchy (shown in figure 10) the materials are disposed of. This would provide a financial incentive to reuse by addressing the current disconnection between the party who pays for a demountable structure (initial owner) and that which benefits from it (final owner).

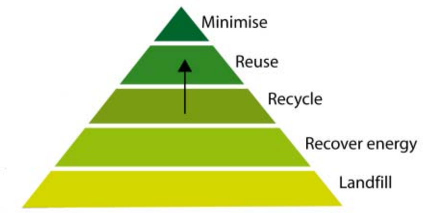


Figure 10: the waste hierarchy, adapted from EU Directive 2008/98/EC (Waste Framework Directive). A higher level of the pyramid represents a more desirable outcome for waste material.

A second strategy could be to encourage, through tax or other incentives, the development of a leasing business model for building materials, where suppliers do not sell beams to contractors, but instead rent them to clients for the lifetime of the building, retaining ownership and thus the right to reclaim them intact at the end-of-life.

These strategies, or others with the same aim, would hopefully increase the occurrence of demountable structures and facilitate reuse in the future, thereby decreasing carbon dioxide emissions from the production of new and recycled steel.

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