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Reclaiming structural steels from the end of service life composite structures for reuse – An assessment of the viability of different methods

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ABSTRACT

The ability to separate structural steel sections from concrete slabs in composite beams without damage forms a key technical challenge for reclaim and direct re-use of composite structures as opposed to recycling. This paper addresses this technical challenge. It presents the results of a feasibility study using a variety of potential techniques, including laser cutting, band-saw cutting, wire-saw and wall-saw cutting, and diamond core drilling, to cut welded shear connectors in conventional steel-concrete composite beams with the steel sheeting perpendicular to the steel section. The most feasible reclaiming method was found to be wire-saw and wall-saw cutting. After reclaiming steel sections, steel tensile coupon tests were carried out on the recovered steel sections and their mechanical properties were compared to those of the original steel used in the composite beams. The coupon test results showed identical behaviour of the original and reclaimed steels. The energy use of the different methods of reclaiming was also recorded to calculate carbon emission and was found to be several orders of magnitude lower than manufacturing virgin steel or recycling steel.

1. Introduction

The majority of steel used at the end of service life (EoSL) in the building sector is recycled to make new steel products (Sansom and Avery, 2014). Whilst steel is endlessly recyclable, much of it is recycled prematurely before the end of its technical life and structural quality (Cooper et al., 2014) and in doing so reduces its physical and economic value (Pomponi and Moncaster, 2017), whilst also losing the embodied energy contained in the products, and adding energy consumption and carbon emission during the melting process (UNEP, 2017). As steel is a product with high carbon footprint and there is increasing demand for steel, finding ways to reclaim and directly re-use steel rather than recycling could make a significant contribution to future low carbon construction, thereby reducing demand for virgin steel and bringing about a paradigm shift from a linear value chain for construction to one based on the principle of circular economy (Hopkinson et al., 2018).

Steel-concrete composite structures in construction, the focus of this paper, are widely used in the construction of multi-storey commercial buildings, owing to their speed of construction, structural efficiency with minimum use of materials, high quality, service integration, and energy efficiency in use (Nethercot, 1998). For example, in the UK, steel-concrete composite construction has achieved over 70% market share in the commercial building sector (Barrett, N., 2022). An analysis of the in-use stocks of structural steel in the UK built environment shows that urban areas contain large quantities of structural steel that have been accumulated over several decades (Ajayebi et al., 2021).

Compared to recycling which is still energy and carbon intensive with a cumulative energy input of 5–8 GJ/t at a melting temperature of 1500° involving re-melting, re-casting and re-rolling to make new steel sections (Harvey, 2021; Allwood et al., 2011), reclaim and direct reuse

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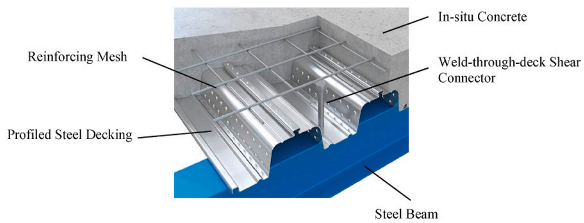

Fig. 1. Main components of steel-concrete composite beam.

significantly reduces potential upstream and downstream environmental impact. In an earlier study, the authors have shown that increasing the share of reusing steel decking could decrease the average aggregated embodied Global Warming Potential (GWP) of steel elements in the construction by 21% (Ajayebi et al., 2020). With over 500 million tonnes of steel being annually recycled worldwide, (SteelConstruction, 2021), the potential for reclamation and reuse of structural steels is high (Taranic, 2016). Reuse is also in line with the new circular economy action plan launched by the European Commission (2020) as the most desirable practice in the circular economy hierarchy except for reducing the use of products. Despite this, less than 7% of EoSL structural steels are reclaimed and reused in the UK (Sansom and Avery, 2014).

Reclaiming and re-using structural steel from easy-to-deconstruct EoSL buildings has been shown to retain the desired technical qualities of steel products, is cheaper and has high carbon saving compared to new steel or recycled steel (Cooper et al., 2017; UKGBC, 2019; Gallego-Schmid et al., 2020; SCI, 2019). As Allwood et al. (2012) says, "All you need to do is unbolt the steel girder from the EoSL buildings and clean it because steel doesn't degrade with use [p4]. A steel-framed EoSL building with bolted connections can be easily disassembled and a number of successful examples have been reported (SteelConstruction, 2021; ICCCE, 2019; Brütting et al., 2019). While for new construction, it is now possible to design for future deconstruction (Sencu et al., 2019; Rios et al., 2015; Ataei et al., 2016).

However, the majority of EoSL steel structures are not easy to deconstruct. Steel-concrete composite structures in construction, the focus of this paper, presents a difficult challenge as the steel beam is welded to the concrete composite floor through shear connectors with very limited accessibility. Previous research has suggested this to be technically complex or impossible without damage to the steel and or concrete (Tingley et al., 2017). This paper presents a fresh attempt to overcome the challenge of separating these two structural components by cutting the welded shear connectors, enabling both the steel and the concrete to be reclaimed as product and re-used. This paper will present findings of a research study to assess the technical feasibility of five different methods of cutting shear connectors.

This paper is structured in four sections. Section 1 outlines the key technical challenges of reclaiming structural steel in steel-concrete composite beams, followed by an introduction to five reclaiming methods. Section 2 provides details of an experimental study to implement these five methods on composite beam segments, the two recommended methods and an assessment of their practicality for implementation on site. Section 3 compares the mechanical performance of reclaimed steel against the original steel and provides data on

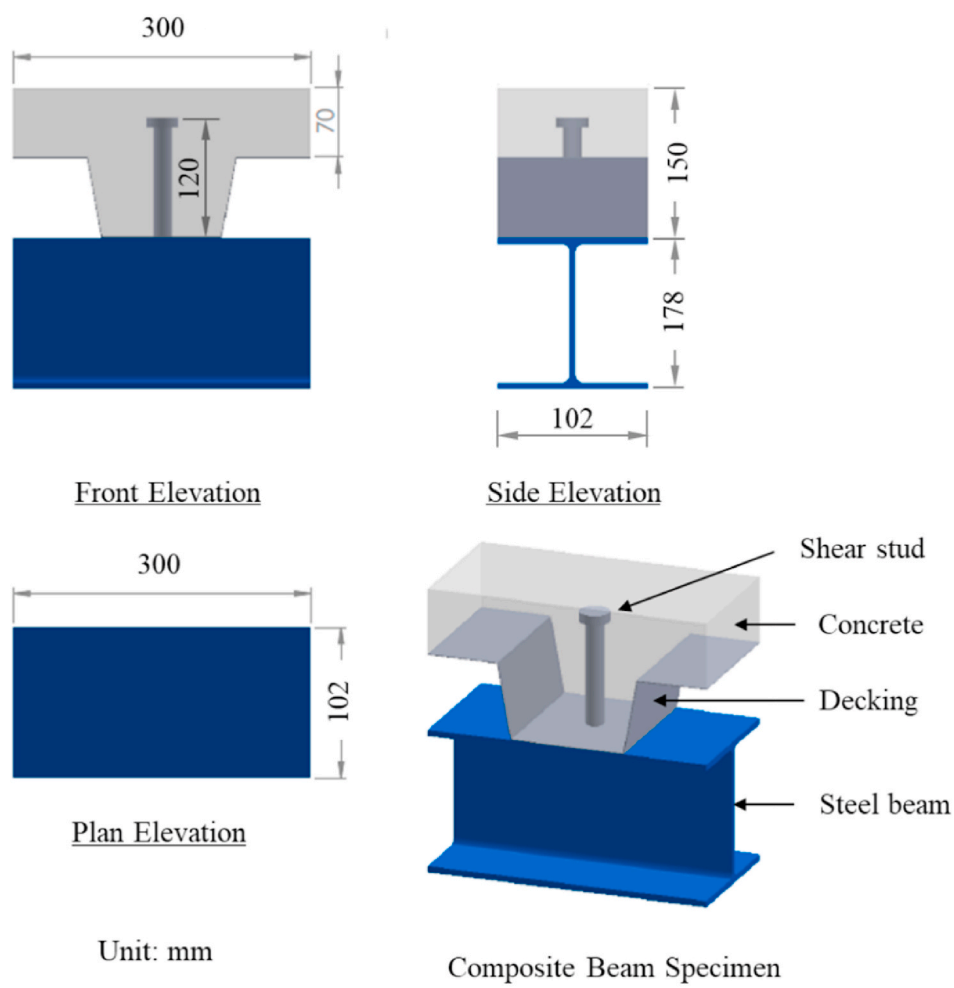

Fig. 2. Schematic view and dimensions of specimens of composite beam segment.

(a) Specimen placement (b) Shear stud welding (c) Specimen before casting (d) Specimen after casting

Fig. 3. Specimen preparation.

environmental performance of the recommended reclaiming processes. Section 4 concludes the study.

1.1. Key technical challenges of reclaiming steel section from steel-concrete composite structure

In steel-framed multi-storey structure, steel is mostly used in steel-concrete composite beams. A composite beam comprises a concrete slab with reinforcing mesh, welded-through-decking shear connectors and a steel section, as shown in Fig. 1.

The shear connectors (studs) transfer shear forces between the steel section in tension and the concrete slab in compression to ensure composite action. The shear studs are easily installed by a firing gun that punches through the steel sheeting and welds the shear stud to the steel section. However, this easy process of construction becomes difficult for the reverse process of deconstruction. To separate the steel section from the concrete slab in the deconstruction process, the shear connectors have to be cut. In this research, five methods of cutting shear connector were investigated. The first method (namely band-saw cutting) is commonly used for cutting steel by steelwork fabricators. The second method (namely wall-saw cutting) is an updated version of the popular steel cutting equipment - metal cutting circular saw. The following presents a brief outline of these methods, as well as the rationale for their consideration. Their detailed assessment, through laboratory testing, is provided in Section 2.

1) Band-saw cutting method: This method can be used to cut irregular or curved shapes, and is highly versatile in uniform cutting action owing to an evenly distributed tooth load. There is minimal cutting wastage, because bandsaws have small "kerf" and narrow blades.
2) Wall-saw cutting method: It is suitable for cutting large items. It is much safer to use by moving along the rail track with a remote-controlled system. Once the tracks are connected, it can make a single straight cut without any length limitation.
3) Wire-saw cutting method: This method is simple to operate and capable of sawing through large-scale construction materials such as reinforced concrete.
4) Core drilling method: The method is simple to operate and can be used on site or in factory. The equipment is versatile, and can be handheld electric, rig mounted, or self-contained trailer. It is light-weight and portable.
5) Laser processing method: Laser cutting offers precision and there is no processing wear problem since the laser head and the work piece do not touch each other.

Table 1
Details of components for all specimens.

Component	Material	Dimensions	Standard
Hot-rolled UB	Steel grade S275	178 mm × 102 mm × 19 kg/m (depth × width of section × mass/m); web thickness = 5 mm; flange thickness = 8 mm.	BS EN 10025-2:2019
Steel decking	Continuously hot-dip zinc coated steel	A combined trapezoidal and re-entrant composite profile; 600 mm cover width, 80 mm depth	Manufactured to BS EN 10346:2009; Designed to BS EN 1993-1-3:2006
Shear stud	Standard mild steel	Φ 19 mm × 120 mm long	BS EN ISO 13918:2008+A1:2021
Concrete	C30/37	70 mm above steel decking	BS EN 206:2013+A2:2021; BS EN 1992-1-1: 2004+A1:2014

2. Detailed assessment of the five cutting methods

Feasibility assessment of the five cutting methods was conducted in the laboratory on small segments of steel-concrete composite beams, as an essential pilot study on the reclamation of the structural steel from the composite beams. The operations on the small-scale laboratory specimens were designed to study the cutting procedure and possible cutting effects to the reclaimed steel beam. It aims to investigate the technical viability of the cutting methods and ready for further implementation on demolition site in the future.

2.1. Laboratory tests

2.1.1. Specimen preparation

Fifteen identical specimens, each representing a segment of steel-concrete composite beam, were prepared for the five cutting methods. Each method was used on three specimens. As shown in Fig. 2, every specimen consists of a universal beam (178 mm × 102 mm × 19 kg/m UB), profiled steel decking of 80 mm in depth, a welded shear stud (Φ 19 mm × 120 mm long) and a concrete slab with 70 mm thickness above the steel decking. Note that any reinforcing steel which would normally

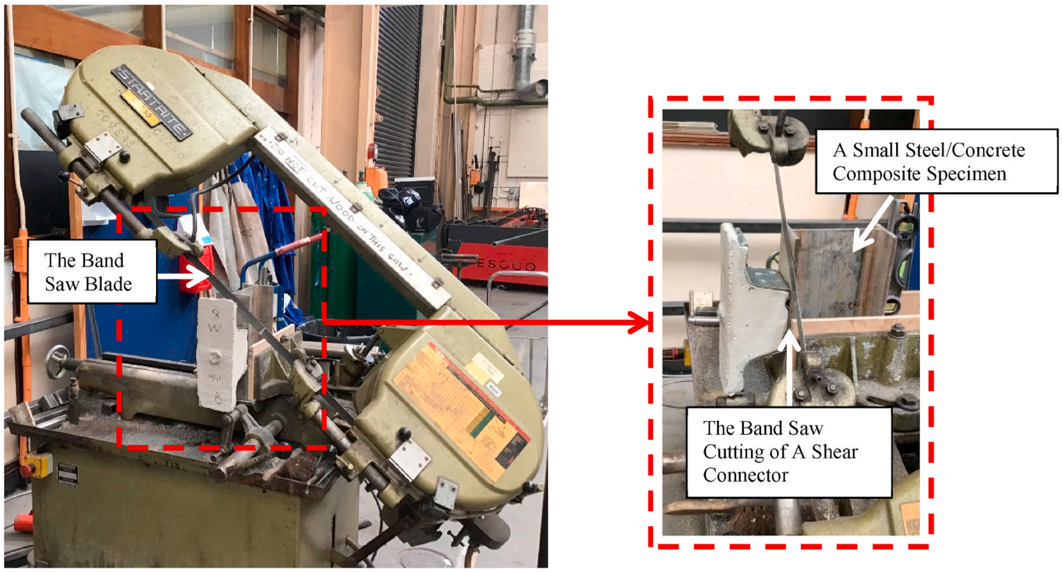

Fig. 4. Band-saw cutting of a steel-concrete composite specimen.

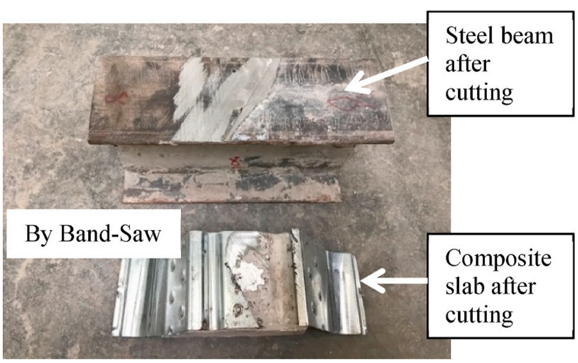

Fig. 5. Surface appearance of a reclaimed steel section by band-saw cutting.

be embedded in the composite slab was not included in the specimen, because it would not affect the cutting process to reclaim the UB section. Fig. 3 shows how each specimen was prepared. Table 1 lists details of the different components of the composite beam segments, made from commonly available commercial products.

2.1.2. Implementation of different cutting methods

2.1.2.1. Band-saw cutting. As can be seen in Fig. 4, a band saw has a long, sharp blade with a continuous band of toothed metal stretched between two or more wheels. In this study, the Startrite Meba metal-working horizontal band-saw cutting machine SM250 was used (Machine Spares Ltd, 2021). Before cutting, a specimen was placed at an angle to the blade. During operation, the 2 thick metal cutting blade moved downwards. Due to tooth size and diagonal angle of the blade towards the steel section, a deep cut was left on the surface of the reclaimed I section as can be seen in Fig. 5. This method needs to be developed further to minimise the surface loss. Furthermore, because the cutting machine has to be fixed, the only way of cutting a long composite beam would involve moving the composite beam horizontally in a guided rail combined with some vertical movement by using a crane, which makes this cutting method not practical.

2.1.2.2. Wall-saw cutting. The wall-saw cutting method employs an

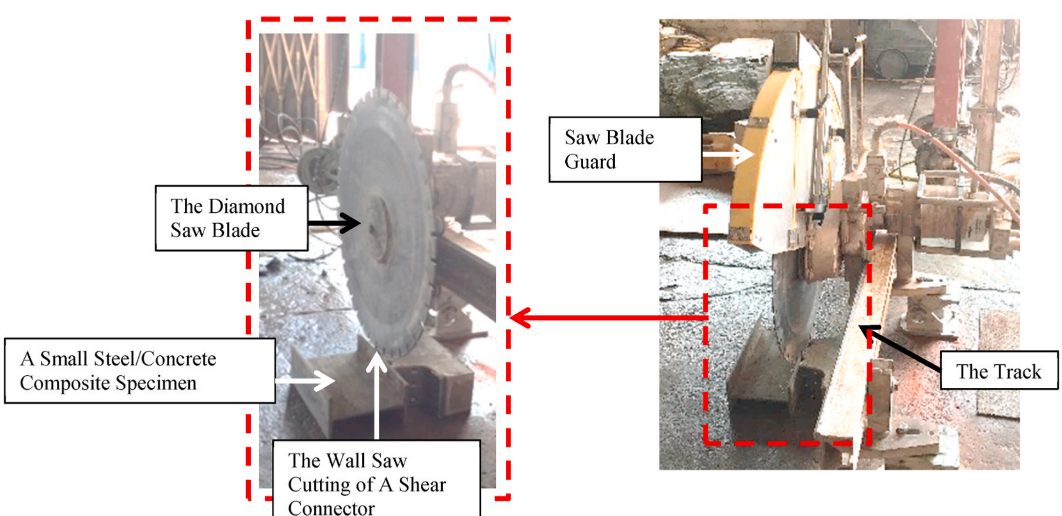

Fig. 6. Diamond wall-saw cutting of a steel-concrete composite specimen.

Fig. 7. Surface appearance of reclaimed steel sections after cutting by diamond wall-saw.

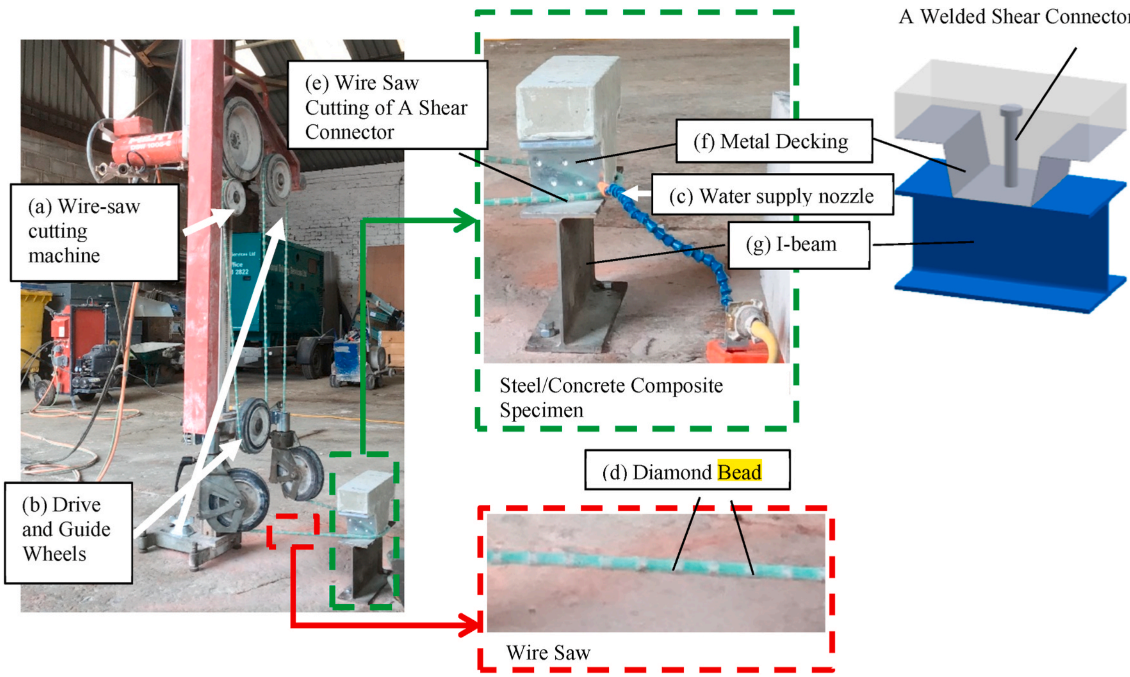

Fig. 8. Diamond wire-saw cutting of a steel-concrete composite specimen.

abrasive circular saw with a diamond blade mounted on a track for precision cutting of hard materials. In this research, the Pentruder 6-12HF wall-saw cutting machine (see Fig. 6) was used (Pentruder UK Ltd, 2021). This machine used a high-frequency motor (18 kW) for cutting. The wall-saw head of the cutting system is lightweight (21 kg) and easy to swap to different blades (Ø800 mm - Ø1200 mm) with a maximum cutting depth of 515 mm.

The machine was anchored on the horizontal laboratory concrete floor. A water-cooling system with water supply nozzles supplied coolant during the cutting process. The entire cutting process was operated by remote control, only requiring the operator to set the location of the cut. The approximate cutting time was 10 s for separation of one shear connector. As shown in Fig. 7, the surface appearance of the reclaimed steel section is good. When cutting a long composite beams, the cutting blade can be moved horizontally along a track.

2.1.2.3. Wire-saw cutting method. The wire-saw cutting method uses diamond wires for cutting. In this research, the wire-saw cutting machine (see Fig. 8 (a)) was Hilti DSW 1005-E with a motor power of 9.4 kW. The basic equipment includes 2 single-pair guided pulley stands and wheels (see Fig. 8 (b)) which can be adjusted in any direction. In this research, the diameter and length of the diamond wires were 8 mm and 2 m respectively. As with the wall-saw cutting method, a water-cooling system for wet wire-saw cutting was used with a flexible water supply nozzle (see Fig. 8 (c)) at the wire entry point on the return side (slack side), located at the front of the object being cut. After anchoring the diamond wire-saw system to suit the cutting position, the operator twisted the wire in one direction so that each diamond bead (see Fig. 8 (d)) would rotate and wore evenly during cutting. The wires cut a controlled arc (see Fig. 9 (e)) between the steel decking and I beam (see Fig. 8 (f) & (g)). As shown in Fig. 9, abrasion of the cutting wires on the steel section caused some removal of material and left an arc appearance on the reclaimed steel surface. However, this was purely some surface effect with minimum reduction in thickness of the flange, as will be

Fig. 9. Surface appearance of a steel section from a composite specimen after cutting by diamond wire-saw.

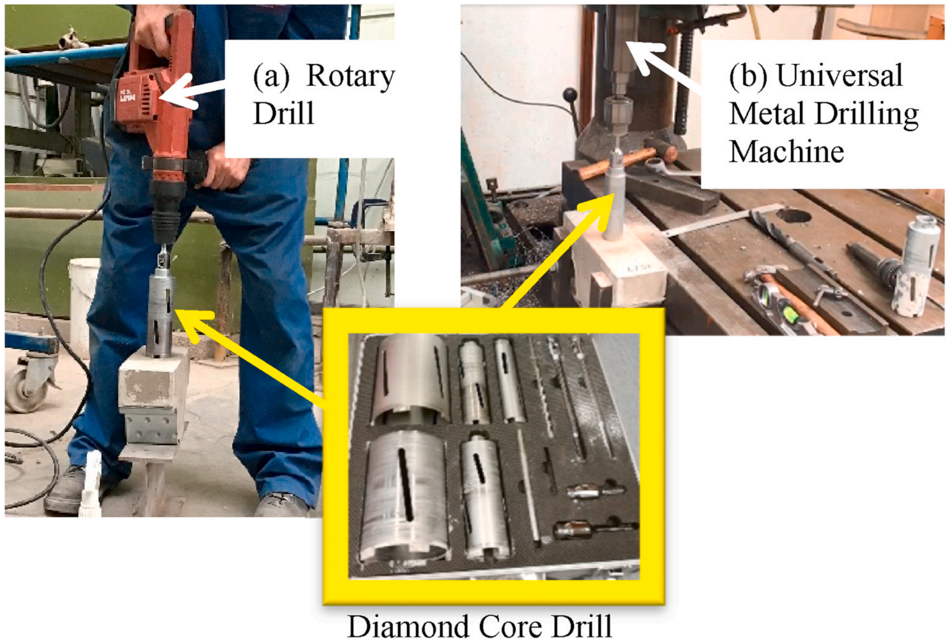

Fig. 10. Two methods using (a) hand-held drill, and (b) lab mounted drill, for diamond core-saw drilling around a shear stud.

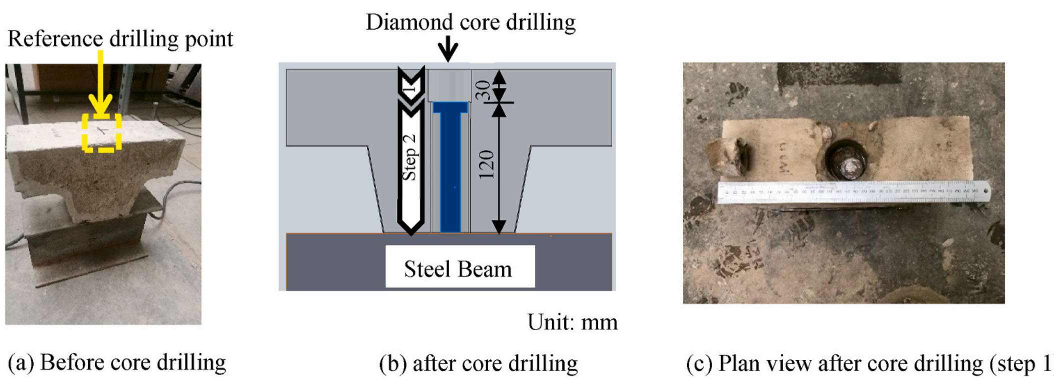

Fig. 11. Diamond core-saw drilling process.

demonstrated by the mechanical properties of the reclaimed steel in Section 3.

2.1.2.4. Core drilling method. This method was envisaged to remove concrete around every shear stud by drilling and then pull the steel section with the drilled core out of the concrete section. The shear studs could then be sheared off one by one. In this research, both the hand-held electric and mounted methods were attempted. In both cases, the diamond drill bit was 52 mm diameter, leaving enough clearance (>20 mm) in case of any off-centred drilling. The hand-held rotary drill (Fig. 10 (a)) was found to be hard to control due to the counter-acting force, necessitating fixing the drill (Fig. 10 (b)). Water cooling was manually applied to ensure that the workspace remained free of dust. A core drilling speed of 4 mm/min was achieved. Thus it took 7.5 min to drill up to the cap position of the shear stud which was 30 mm from the slab surface. Due to this slow speed in drilling, which would render the process impractical, the drilling process did not continue to the root of the shear stud, which would have taken 30 more minutes to drill an additional 120 mm to reach the root of the shear stud on the flange of the steel section, as illustrated in Fig. 11 (b).

2.1.2.5. Laser drilling. The intention was to use the high and concentrated energy of laser to remove the concrete around the shear stud to break the bond between these two materials so that the steel section could be pulled out of the concrete block, as envisaged in the core drilling method.

In this research, a 16 kW laser processing facility (IPG multi-mode ytterbium fibre laser with a 6-axis Kuka robotic manipulation system) was employed as shown in Fig. 12.

In fact, laser cutting had been proposed to cut welded shear studs to separate steel and concrete in composite construction (Peter et al., 2018). Due to the large thickness of the concrete around the shear stud, multiple laser passes were necessary to ensure that any molten material could be removed by blowing air or gas, similar to observations by others (Seo et al., 2020; Muto et al., 2007; Crouse et al., 2004). Vaporizing the material, instead of melting, would have required many times more energy.

A laser penetration speed of 5 mm/min was achieved. Following laser melting, the melt pool was solidified into a glassy phase which was brittle. This was easily removed with a mechanical chisel. Thus, it took 6 min to expose the cap of the steel stud (30 mm from the concrete surface) as shown in Fig. 13 (c). As with core drilling, due to complexity and slow speed, laser drilling was not continued as this would not be a practical solution for reclaiming steel from composite beam.

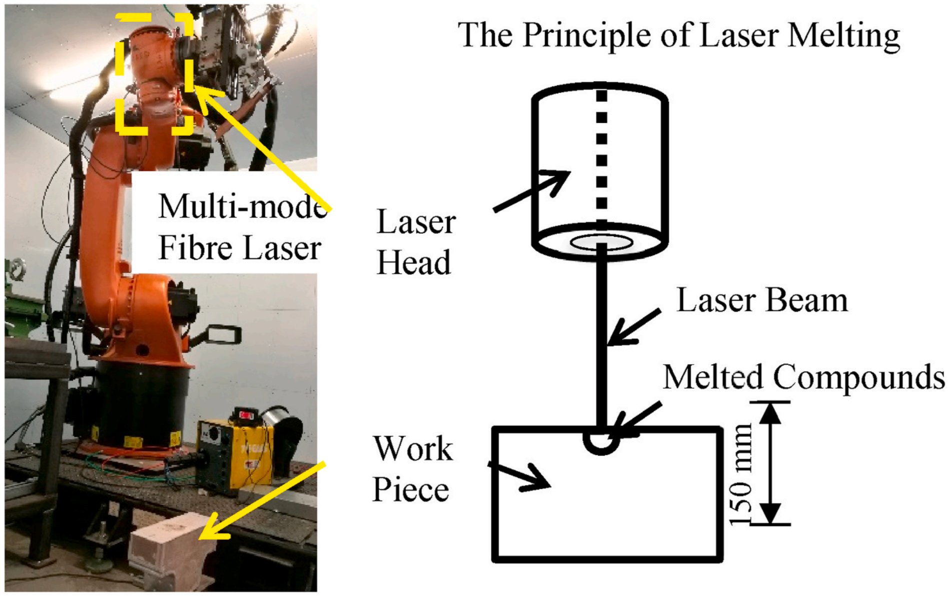

Fig. 12. Laser processing facility and illustration of its principle to deconstruct a composite beam.

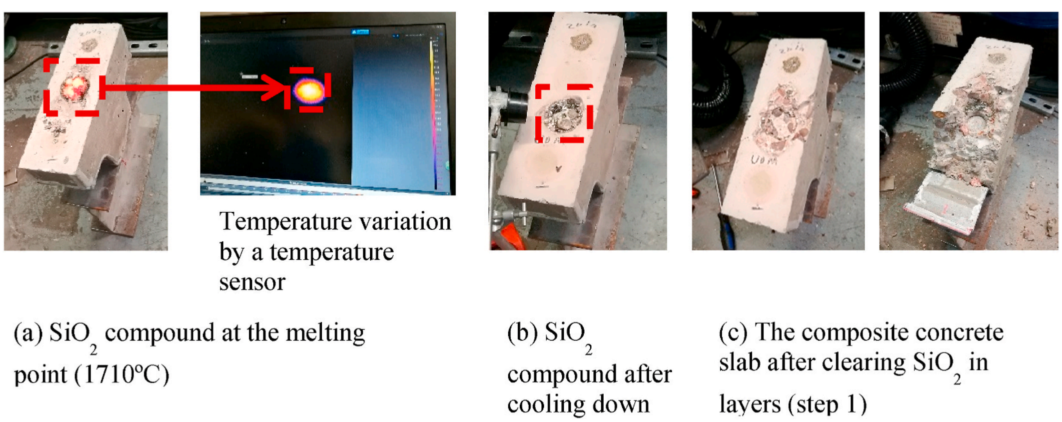

Fig. 13. Laser melting process of concrete.

Table 2
Comparison of five methods of reclaiming steel section.

General requirement	Wall-saw cutting	Wire-saw cutting	Band-saw cutting	Core drilling	Laser drilling
a) easy to implement (rate of success)	100%	100%	70%	–	–
b) speed[a]	10 s	6 s	8 s	37.5 min[c]	30 min[c]
c) defect (thickness loss of the reclaimed steel[b])	0.5 mm	1 mm	max. 3 mm	–	–
Reclaiming potential	high	high	low	none	none

[a] Approx. cutting time for separation of one shear stud.
[b] The flange thickness was 8 mm.
[c] Estimation only without completion.

2.1.3. Summary

Table 2 assesses the five different reclaiming methods, based on comparison of the following performance criteria: (a) easiness to implement; (b) speed; and (c) defect, where defect is the thickness loss of

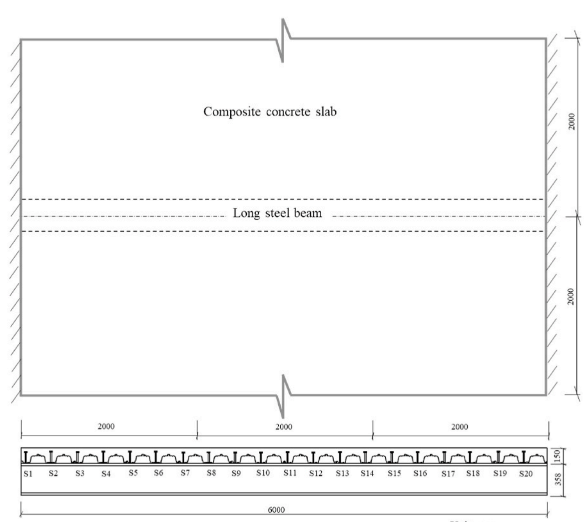

Fig. 14. An illustrative composite beam.

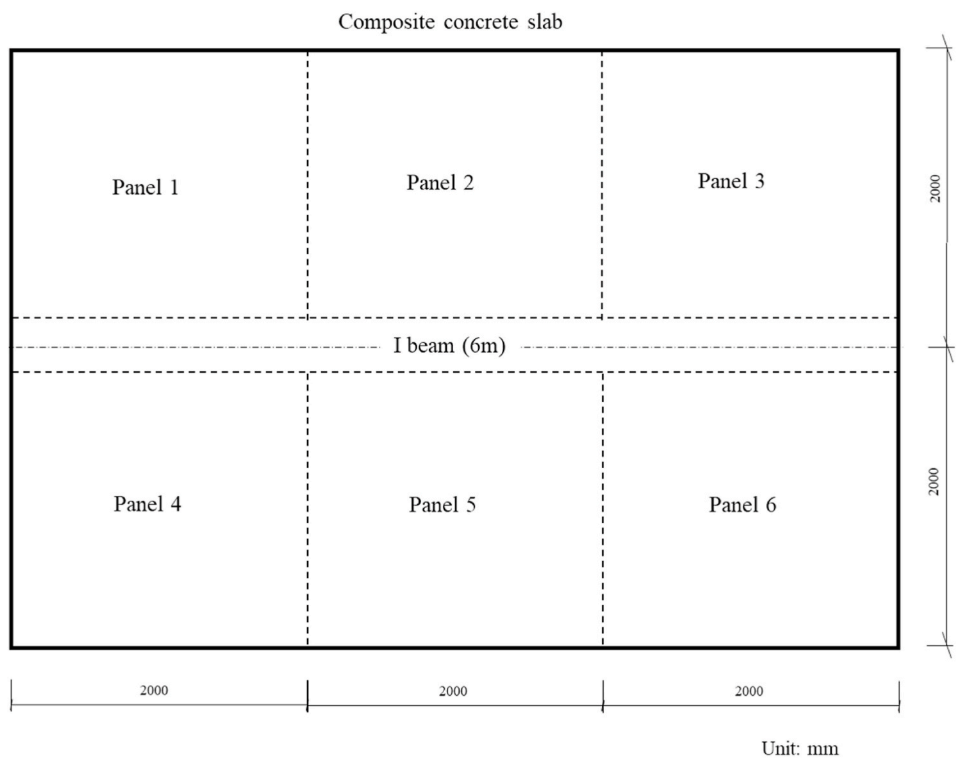

Fig. 15. Plan of cutting the composite floor in Fig. 14 to six panels and a composite beam by wall-saw cutting.

the reclaimed steel. Core drilling and laser drilling are clearly unlikely to be used. Wall-saw cutting and wire-saw cutting are two feasible methods. Among these two feasible methods, wall-saw cutting would be preferred as it would be easy to control the process on long specimens and it results in less damage to the steel section, albeit with a slight reduction in speed of cutting a shear stud compared to wire-saw cutting.

2.2. Recommended implementation in practice

The results of the laboratory trial tests, described in the previous section, have concluded that wall-saw and wire-saw cutting methods could be used to separate steel from concrete in short steel-concrete composite beam segments. When dealing with large sizes of composite beam in demolition, a wall-saw cutting machine is recommended to cut the large slab into small panels. Either a wall-saw cutting or wire-saw cutting method is recommended to separate steel from concrete in steel-concrete composite beams. The concrete slab cutting has been proved to be practical and efficient on site. Similar sizes of the composite slab have already been successfully cut and removed in hours on site in a concrete demolition project, by using wall-saw cutting and crane lifting (Precision Cutting & Coring LLC., 2016).

This section will explain how these methods may be implemented in practice. Consider a fictitious full-scale composite slab illustrated in Fig. 14 with a span of 6 m and width of 4 m. The task is to reclaim the long steel beam in the centre of the slab. There are 20 through-deck-welded shear studs. The profiled steel decking is perpendicular to the longitudinal axis of the beam.

The proposed sequence of operation to reclaim the steel section is as follows: (1) disconnect the slab from the steel frame by cutting the slab into six panels as indicated by the dotted lines in Fig. 15. A wall-saw cutting machine is recommended to cut along these dotted lines. (2) lift and remove of the six panels in order by a crane. Fig. 15 demonstrates the cutting and removing order of the six smaller panels (2 m × 1.9 m) out of the composite slab in Fig. 14 (6 m × 4 m). Crane rigging is used with four holes bored though each panel to support it during cutting and lifting by the crane; (3) disconnect and remove the remaining skeletal composite beams from the steel frame by unbolting of the connections; (4) separate the steel section from the residual concrete either on site or transport into factory using wall-saw cutting or wire-saw cutting as described in the previous section.

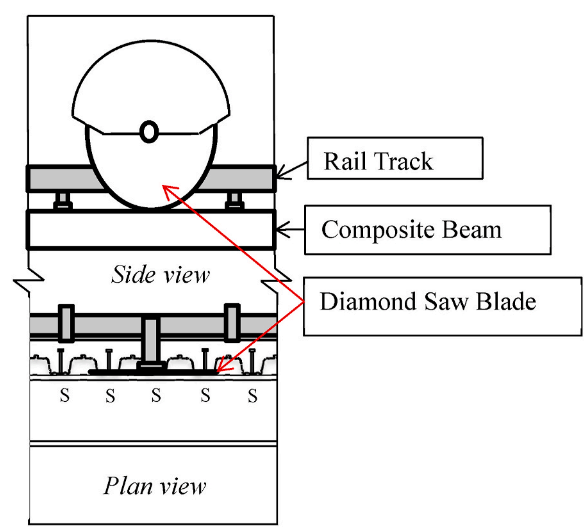

Fig. 16. Plan and side views of wall-saw cutting of a long composite beam.

For wall-saw cutting the 6 m long beam, as shown in Fig. 16, the wall-saw blade mounted on a rolling track moves longitudinally to cut the long beam with a row of shear studs. Both flanges of the beam are fixed to the ground similar to that in Fig. 6.

For wire-saw cutting the 6 m long beam, the diamond wire can be passed through gaps between the profiled steel decking and the steel section. By using a diamond wire of minimum 5 m length, a group of shear studs (3–5 studs) can be cut in one turn, as sketched in Fig. 17. Thus the 6 m steel beam with 20 shear studs can be reclaimed by four repeated wire-cutting in few minutes. The lower flange of the full-length

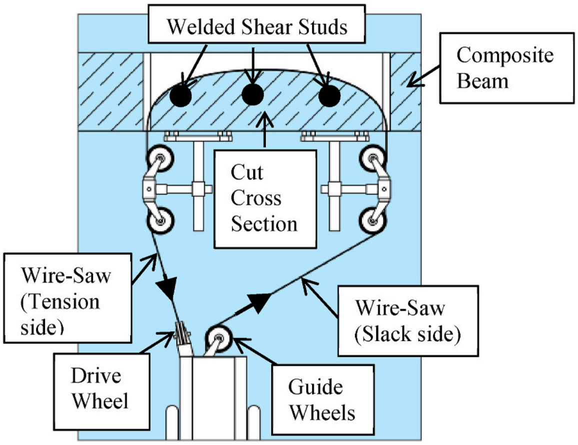

Fig. 17. **Plan view of wire-saw cutting of a long composite beam.**

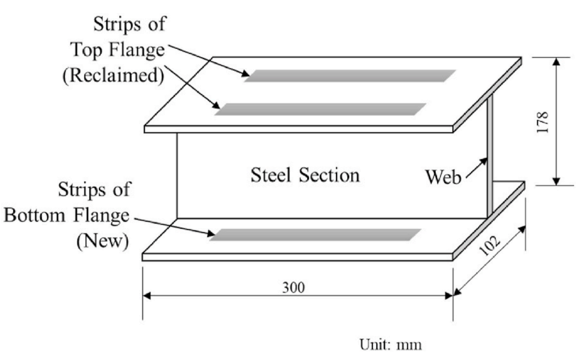

Fig. 18. **Positions of tensile coupon specimens.**

steel beam is clamped on the ground similar to that in Fig. 8.

3. Performance of reclaimed steel

3.1. *Mechanical properties of reclaimed steel*

The heating associated with welding and cutting can lead to a change in microstructure and therefore a strength reduction of the steel (Brätz and Henkel, 2019). Fig. 3 (c) shows the heat affected zone (HAZ) produced during the drawn arc stud welding process. In addition, the mechanical wire-saw/wall-saw cutting process in steel reclamation can further influence the characteristics of the steel since the majority of the energy converts into heat. It is important to ensure confidence in the quality of the steel that the reclaimed steel does not suffer any reduction in mechanical properties. In this research, tensile coupon tests were conducted to compare the mechanical properties of reclaimed steel and the original steel.

Fig. 18 shows position of steel coupons from the reclaimed steel sections (from the top flange where was welded to the shear stud) and original steel (from the bottom flange). Any surface roughness (due to cutting) or surface anti-rust coating was removed by milling and grinding the surface to achieve a smooth finish before the tensile coupon testing. Fig. 19 shows the dimensions of a representative tensile coupon specimen with a gauge length of 60 mm, with the dimensions conforming with BS EN ISO 6892-1 (2019).

Uniaxial tensile testing of the steel coupons was carried out in accordance with the provisions of BS EN ISO 6892-1 (2019), as shown in Fig. 20. The longitudinal tensile strain was measured using a strain gauge, an extensometer and LVDT (Linear Variable Displacement Transducer) embedded in the testing equipment.

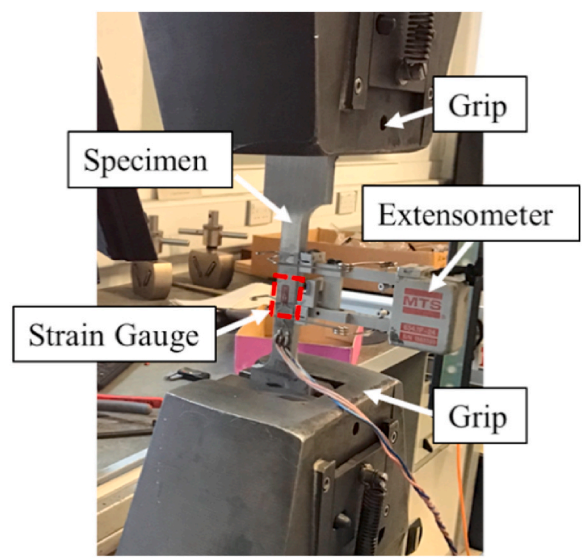

Fig. 20. Tensile testing set up.

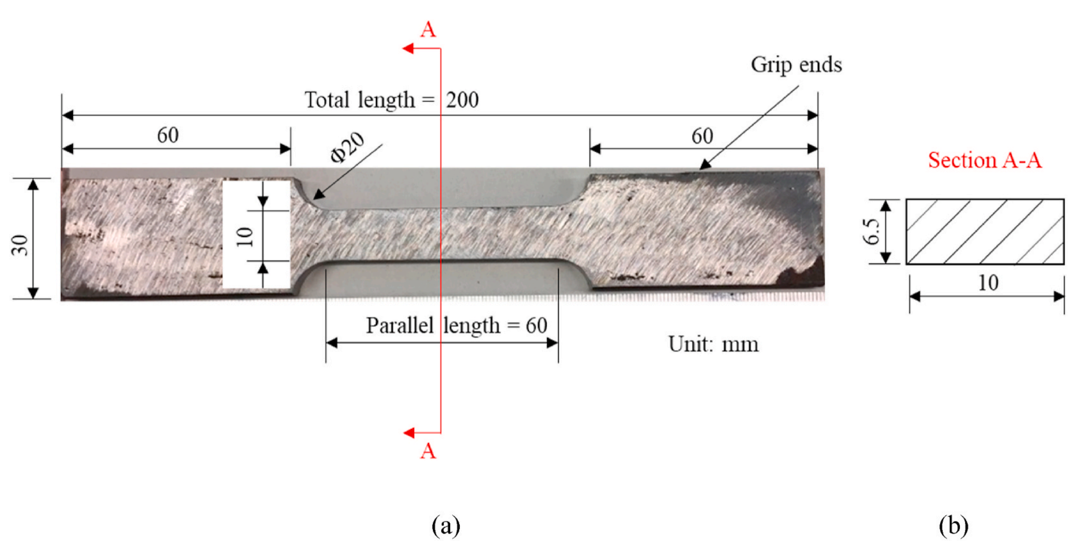

Fig. 19. (a) Plan view of a steel coupon (b) Cross-section of the gauge length region.

Table 3
Summary of results of tensile coupon tests on original and reclaimed steels.

Specimen description	Number of coupons	δ[a] (%)	SD[b], δ	E[c] (GPa)	SD, E	Av. f_y [d] (MPa)	SD, f_y	Minimum f_y (MPa)	Av. f_u [e] (MPa)	SD, f_u
Original steel (S275)	5	18.8	6.2	211.6	17.0	319.1	11.7	308.7	465.6	8.3
Reclaimed steel by wall-saw cutting	5	20.4	6.0	211.1	11.3	297.4	16.1	286.0	463.8	12.4
Reclaimed steel by wire-saw cutting	5	25.3	0.2	210.7	1.7	334.0	17.3	279.3	461.2	16.8

[a] Elongation of the steel coupon during test.
[b] Standard deviation for elongation.
[c] Modulus of elasticity.
[d] Average yield stress of the steel.
[e] Average ultimate tensile stress of the steel.

Table 4
Summary of electricity and water consumption during reclaiming operations for the fictitious structure shown in Fig. 14.

Procedure	Initial state	Final state	Detailed Description	Method	Motor power (kw)	Electricity usage (MJ/kg)	Water usage (kg)
P1: Cutting slab	Large slab (6 m × 4 m)	Small panels (2 m × 1.9 m)	Cut large slab, into small panels	Wall saw	15	0.066	99.9
P2: Cutting beam	Composite beam (6 m)	Steel beam (6 m)	Separate steel beam from composite beam	Option 1: Wall saw	15	0.009	13.3
				Option 2: Wire saw	9.4	0.006	16.7
P3: Cleaning	–	–	Steel surface cleaning by grinding	Grinder	0.7	0.0004	0
Procedure Summary	**Initial state**	**Final state**	**Option**	**Method**	**Motor power (kw)**	**Electricity usage (MJ/kg)**	**Water usage (kg)**
P1–P2	Large slab	Steel beam	Reclaiming-Option 1	P1–P2: Wall saw	30.7	0.075	113.3
			Reclaiming-Option 2	P1: Wall saw P2: Wire saw	25.1	0.072	116.6

Table 5
Comparison of environmental performance for the reclaiming methods against steel manufacturing.

Process	Method	Motor power (kw)	Energy consumption (MJ/kg)	Emissions contributing to Global Warming Potential (kg CO_2eq/kg)
Manufacturing	Manufacture of new steel (total embodied)	N/A	20.1[a]	2.39
Reclaiming-Option 1	Pure wall-saw cutting (electricity on site)	30.72	0.0749	0.0173[b]
Reclaiming-Option 2	Wall-saw combined with wire-saw cutting (electricity on site)	25.12	0.0716	0.0166[b]

[a] Retrieve data from World Steel Association (2017)
[b] Embodied carbon of average UK low voltage electricity grid mix (ecoinvent 3.3, 2018).

Table 3 summarises and compares the tensile properties of the original steel and reclaimed steels using wall-saw and wire-saw cutting, giving average and standard deviation for elongation (δ), modulus of elasticity (Young's modulus, E), yield stress (f_y) and ultimate tensile stress (f_u).

The results indicate that there are no significant influence of the heating processing during welding and cutting for reclamation. There is almost negligible difference in the Young's modulus (E) of the steel reclaimed by the two methods. Compared to the original steel, the reclaimed steel by wire-saw cutting achieves a slight increase of the average yield stress (Av. f_y), while the reclaimed steel by wall-saw cutting suffers a slight reduction in the average yield stress. The standard deviation for average yield stress (SD, f_y) for the reclaimed steel by the two methods is slightly higher, but still achieving the minimum strength of 275 MPa for the grade of the steel, therefore this would not affect the design strength of the reclaimed steel. The ultimate tensile strength of the reclaimed steel by wall-saw cutting is almost identical to that of the original steel while that by wire-saw cutting is with a negligible reduction.

However, as shown in Section 2.1, wall-saw cutting results in very small loss of thickness of the steel (less than 0.5 mm), while wire-saw cutting reduces the steel flange by about 1 mm (12.5% of the original steel thickness of 8 mm).

3.2. Environmental impacts of reclaiming processes

In this study, the environmental impacts of reclaiming steel using wall-saw cutting and wire-saw cutting methods are based on the consumption of electricity in cutting and water usage in cleaning. Using the fictitious slab in Fig. 14 as example, Table 4 summarises their usages.

Table 5 converts the electricity and water consumptions into equivalent global warming potential and compares the results of the two reclaiming methods with that of the original steel manufactured from raw and recycled resources. The embodied carbon of a typical new steel section produced in Europe is obtained from the Worldsteel LCA Methodology Report (World Steel Association, 2017). The embodied emissions of the energy consumption of reclaiming activities are calculated by using the SimaPro tool version 9.0.49 and the dataset of ecoinvent 3.3 for low voltage UK average grid mix.

It can be seen that the reclaiming operations are two orders of magnitude lower in their environmental impacts (0.4%).

4. Conclusions

The reuse of structural components (e.g. steel members) over multiple service lives reduces demand for virgin material usage, energy consumption and environmental impact of building structures. This paper presents five potential reclaiming methods to overcome the difficult challenge of accessing and cutting weld-through-deck shear connectors to reclaim the structural steel section from composite beam for reuse. The reclaiming techniques include band-saw cutting, wire-saw cutting, wall-saw cutting, laser drilling and diamond core drilling. These reclaiming methods were implemented in laboratory trial tests to reclaim the steel sections from small-scale composite specimens.

The trial tests on small-scale steel-concrete composite beams have proven that reclaiming load-bearing steel members from EoSL composite beams is technically viable. The small-scale laboratory results from using five techniques found that wire-saw and wall-saw cutting methods were the most feasible reclaiming methods. They both successfully disconnected the shear connector between the concrete slab and the steel section of the composite segments with little adverse effect on appearance of the reclaimed steel section other than a few tiny chips on the surface of the reclaimed steel section. In contrast, the band-saw method needs to be developed further in the cutting angle and length since using this method left a deep indentation on the surface of the reclaimed steel section. Furthermore, an industrial version of the band saw suitable for use along long lengths of beam would need to be developed and integrated into the steel handling equipment such as motorised tables. The laser processing and core drilling methods are not recommended. Between wall-saw cutting and wire-saw cutting, using wall-saw cutting is preferred because it would result in minimum loss of the steel surface. The tear and wear of the consumables/blades has not been investigated in this study due to limit number of samples. It can be further studied in the future.

Based on tensile coupon tests of the original and reclaimed steel, the mechanical properties (Young's modulus, yield strength, elongation, ultimate tensile stress) of the reclaimed steel are very similar to those of the original steel.

The amount of energy consumed using the recommended methods of reclaiming, when converted to equivalent global warming potential, is about two order of magnitude lower than that of the embodied carbon contained in making the steel, based on reclaiming a steel section from a 6 m by 4 m slab.

This study provides a proof of concept and demonstrates the technical feasibility, quality assurance and potential benefits of reclaiming steel from existing steel-concrete composite beams, which had previously been considered impractical. Further researches on reclaiming beams from a full-scale composite slab are required to identify and overcome all practical obstacles.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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