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Information paper – 31
Embodied carbon of steel versus concrete buildings

Prepared by:
David Clark & Dan Bradley

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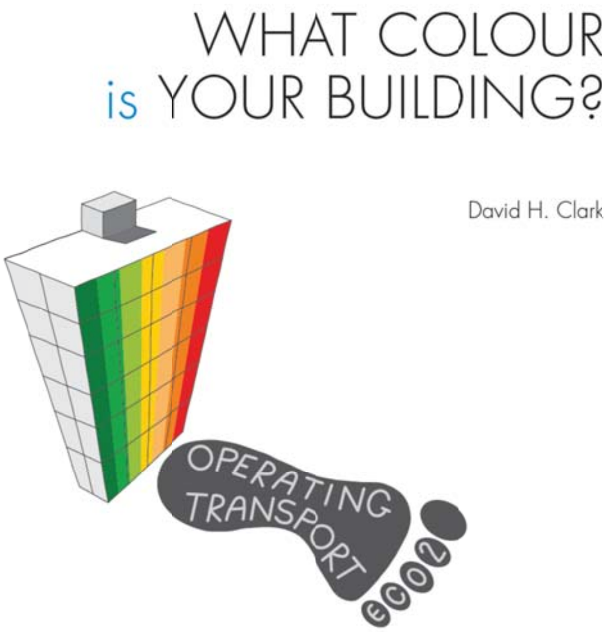

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This information paper is one of a series of papers written during the preparation of the book **What Colour is Your Building?** (www.whatcolourisyourbuilding.com). The papers do not form part of the book and have not been peer reviewed. They provide further technical detail, analysis and information to support statements made in the book. All of the papers can be downloaded from www.wholecarbonfootprint.com.

Embodied carbon of steel versus concrete buildings

This information paper provides a summary of the various embodied carbon studies comparing steel and concrete framed buildings listed in Section J4 of Appendix J. The views of various trade organisations referred to in Chapter 8 are also summarised.

1. SUMMARY OF PUBLISHED CASE STUDIES ON EMBODIED CARBON

Figure 1 (a copy of Figure J.1 in Appendix J) shows the embodied carbon estimates from different studies for two typical suspended floor systems: composite slab on steel frame, and concrete slab on concrete frame. The data was sourced from:

- IStructE research paper – Concrete Centre / Arup, 2012.
- Sustainable Concrete Architecture – David Bennett, RIBA Publishing, 2010.
- Steel Construction Industry – Eaton & Amato, 1998.
- British Constructional Steelwork Association – Target Zero Office study, 2011.
- Cundall R&D project, 2013.

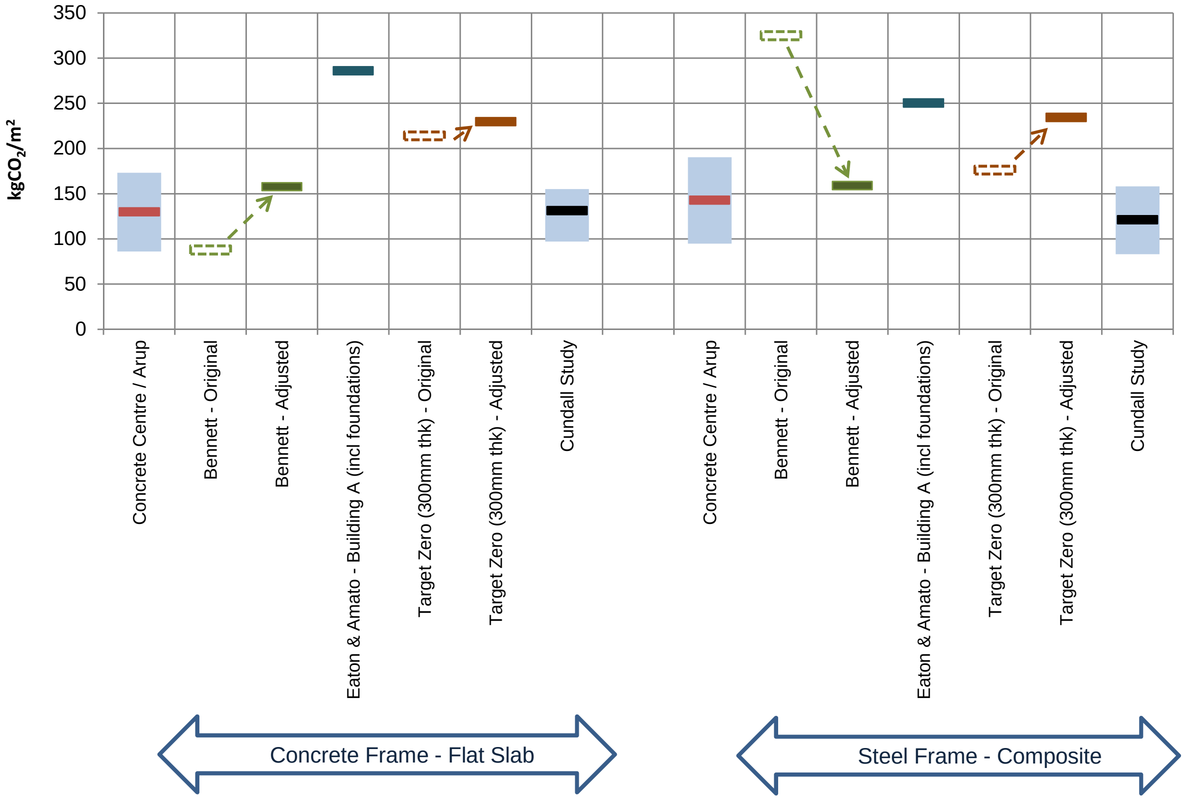

Fig 1 **Comparison of embodied carbon values ("cradle to site") for steel and concrete superstructure**

Please note that this is not a scientific comparison, and does not attempt to state which values should be used. Instead, the aim is to highlight the wide range of results from different studies of similar structures. The values, except for Eaton & Amato, exclude substructure. For simple pad footings, this can be equivalent to 15% of the superstructure for concrete frames and 10% for steel frames (which are lighter). The additional embodied carbon for basements and ground floor slabs would be similar for both types of structure.

After making some simple adjustments of the steel and concrete ECO_2 factors used in two of the studies (unadjusted values are shown dotted in Figure 1), there appears to be little difference between an efficient steel framed structure and an efficient concrete structure.

Details on the various studies are provided below.

Concrete Centre & Arup, 2012

In 2010, Arup undertook a 'cradle-to-site' embodied carbon study of eight common floor slab configurations for the Concrete Centre.[1] Six short span (7.5 m x 7.5 m grid) and two long span (15 m x 7.5 m grid) were assessed in a generic six storey office building with a gross floor area of 16,480 m^2 – refer to Figure 2. The short spans were also assessed for two storey school and hospital buildings.

Fig 2 Structural slab options chart (image courtesy of The Concrete Centre)

The study considered two variables for each of the floor options with the values shown in Table 1:

- Specification – the type of materials used (e.g. 40 MPa concrete with 50% ggbs is 'low spec' while a 100% Portland Cement concrete is a 'high spec').

- Methodology – the carbon emission factors used for each material due to different cradle-to-gate calculation methodologies (as noted earlier there can be a wide range in values for the same material, particularly for steel). This could be considered to be the range of uncertainty in the data.

	Cradle to gate embodied $kgCO_2$ / tonne				
Study type	Base case	Specification study		Methodology study	
Material	*Typical*	*Low*	*High*	*Low*	*High*
C32/40 concrete	110	67	157	110	110
C25/30 concrete	95	59	133	95	95
Post-tensioned concrete	166	150	182	119	190
Lightweight concrete	168	125	215	106	223
Reinforcement	872	872	872	430	1,770
Steel	1,770	1,770	1,770	1,360	2,750

Table 1 **Cradle-to-gate $kgCO_2$/tonne for materials used in the study (source: Concrete Centre / Arup)**

Figure 3 shows the variation in embodied carbon for the structure for all of the building types.

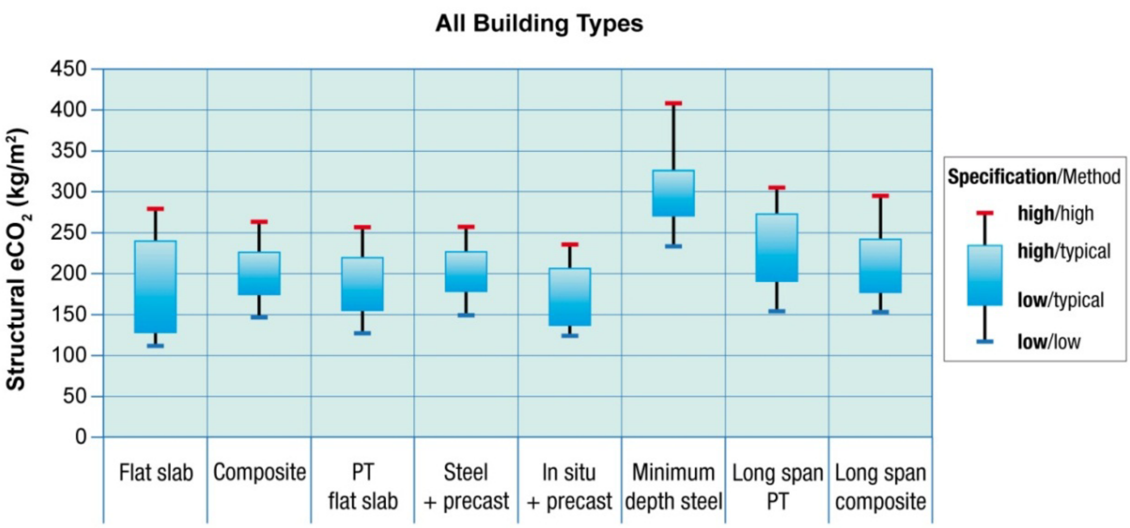

Fig 3 **Comparison of embodied carbon (superstructure + substructure) for structural framing options across all the building types (source: Concrete Centre / Arup)**

For the office building the mean embodied carbon was 340 $kgCO_2/m^2$, with the structure accounting for approximately 60% of this. The highest carbon structure was Slimdek and the lowest were the in situ concrete and steel & precast options. The range in calculated embodied carbon is shown in Table 2.

	$kgCO_2/m^2$
Whole office building	300 to 410
Superstructure only (excluding foundations & ground slab)	110 to 220
Total structure	170 to 280
Non-structural elements (excluding construction & services)	92 to 98

Table 2 Range in calculated embodied carbon for office buildings (source: Concrete Centre / Arup)

Some of the key findings from the study were:

- There was little difference between typical steel and concrete framed buildings, with concrete having arguably a slightly lower impact.
- A value of 200 $kgCO_2/m^2$ could be adopted as a rule of thumb for the embodied carbon in the structural elements (in typical regularly framed medium rise structures without basements).
- Structures where embodied carbon exceeds 250 $kgCO_2/m^2$ should be investigated to see if savings can be made.
- The specification of concrete caused the largest variation in impact.
- Slimdek (minimum depth steel) consistently had the highest embodied carbon.
- Long spans were typically around 20% higher embodied carbon than short spans.

A structural engineer, by designing structurally efficient solutions and specifying lower carbon concrete, can make savings of up to 100 $kgCO_2/m^2$ although 50 $kgCO_2/m^2$ might be more typical. This is similar to the emissions due to 6 to 12 months operating energy consumption in a typical office building (refer to Chapter 2 of the book).

Bennett, 2010

In an example embodied carbon audit in the book *Sustainable Concrete Architecture* by David Bennett, RIBA Publishing 2010, steel framed buildings were shown to have three times the embodied carbon of concrete framed buildings. A closer inspection of the input data reveals that a high embodied carbon (ECO_2) emission factor was used for steel, and relatively low ECO_2 factors for concrete (based on 50% ggbs) and reinforcement, compared to the values in the ICE v2 database.[2]

An adjusted calculation (refer to Table 4) for the superstructure of the three storey building, using ICE v2 database values (refer to Table 3), shows that the difference between the two options has reduced significantly, to less than 1%.

	Unit	Bennett ECO_2 factor	Adjusted ECO_2 factor	Comment on adjusted factor (from ICE v2)
Concrete	$kgCO_2/m^3$	156.4	326	C32/40 with 25% ggbs ($133kgCO_2/t$) *
Steel	$kgCO_2/t$	5,216	1,530	UK average
Reinforcement	$kgCO_2/t$	485	770	
Steel decking	$kgCO_2/m^2$	29.1	21.5	Based on UK ave steel

* 50% ggbs is not typically used in concrete mixes in buildings due to the extended time to gain strength. For a fairer comparison of the steel and concrete buildings a 25% ggbs mix was assumed for the adjusted calculation.

Table 3 **ECO_2 factors for original (Bennett) and adjusted (ICE v2) study used in Table 4**

	Original (tCO_2)			Adjusted (tCO_2)		
	Concrete	Steel	Total	Concrete	Steel	Total
Suspended floor slab	209	92		435	191	
Reinforcement (inc walls/columns)	77	7		122	11	
Formwork to slabs	32	-		32		
Steel decking	-	123			91	
Floor only	**317**	**222**		**589**	**293**	
Concrete beams	0.3	-		1		
Concrete columns	14	-		29		
Concrete walls	8	-		16		
Formwork to walls, beams & columns	9	-		9		
Steel framework	-	1,085			318	
Baseplates & bolts	-	5			2	
Fire casing to beams & columns	-	36			36	
Total for beams, walls & columns	**31**	**1,126**		**55**	**356**	
Total superstructure	**349**	**1,348**		**644**	**649**	

Table 4 **Original and adjusted calculation for embodied carbon of three storey building based on Bennett calculations**

Eaton & Amato, 1998

A Comparative Environmental Life Cycle Assessment of Modern Office Buildings by K J Eaton and A Amato, SCI Publication 182 was published by the Steel Construction Institute in 1998. The embodied carbon for two typical offices, Building A (4 storey, 2,600m²) and Building B (8 storey, 18,000m²), were calculated for five different structural options:

- 2 x concrete – reinforced concrete frame & slab, precast concrete & hollow core units.
- 3 x steel – slim floor beams & hollow precast, composite beams & composite slabs, cellular beams & composite slabs.

Figure 4 shows the breakdown of results. One of the conclusions of the report was: '*There is no significant difference between the embodied CO_2 of steel framed office buildings in comparison with concrete framed office buildings.*'

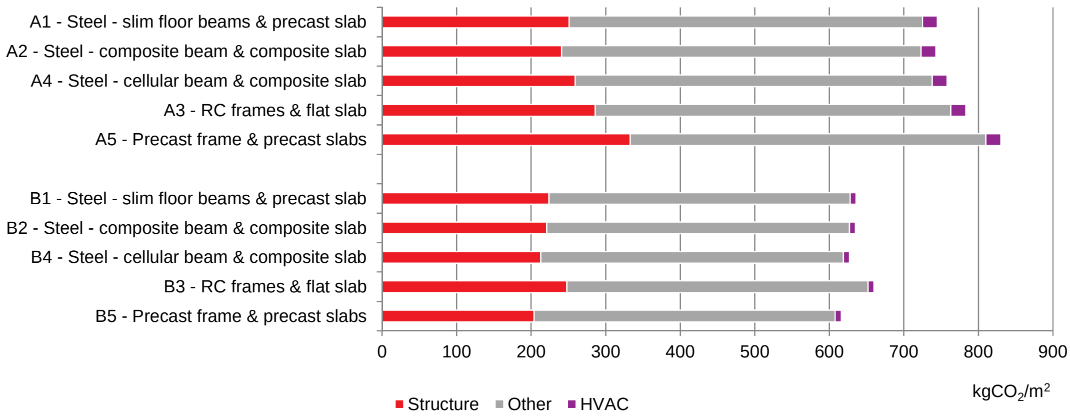

Fig 4 **Embodied carbon results from Eaton & Amato study (source: SCI, 1998)**

Target Zero Office Study, 2012

Chapter 10 of *Embodied Carbon from Target Zero: Guidance on the Design and Construction of Sustainable Low Carbon Office Buildings*, Report V2.0, January 2012 contains data prepared by AECOM and Cyril Sweet.[3]

The conclusion for the office building, based on One Kingdom Street in London, was that '*the above ground post-tensioned concrete structure has 21.5% more embodied carbon than the base case building steel structure.*' The study assumed an ECO_2 factor for steel of 1009 $kgCO_2/t$. If a value of 1,530 $kgCO_2/t$ was used, the UK average factor from ICE v2, then the adjusted results are as shown in Table 5.

	Steel option	Concrete option
Original total superstructure (tCO_2)	**5,812**	**7,062**
Mass of steel (tonnes)	3,700	1,000
Original steel embodied (tCO_2)	3,733	1,009
Adjusted steel embodied (tCO_2)	5,661	1,530
Increase	1,928	521
Adjusted total superstructure (tCO_2)	**7,740**	**7,583**

Table 5 **Target Zero embodied carbon study – results using ICE v2 steel ECO_2 factors**

Now the concrete is marginally better than steel. The results all depend on which ECO_2 factors are selected for the key materials. It should be noted that the building assessed is based on a 12 m x 10.5 m grid which would typically make a 300 mm thick post-tensioned slab an uneconomic choice of structural solution. In the UK the building would usually be steel framed irrespective of what the embodied carbon study stated.

Cundall R&D embodied carbon study

Structural designs were prepared for a typical 7.5 m x 7.5 m office floor grid by Cundall so that the embodied energy of each could be compared. Figure 5 shows the typical layout. Not all options included every beam (e.g. flat slabs have no beams). The floor loadings were 1.5 kN/m^2 for superimposed dead load and 5 kN/m^2 for live load. The floor options were:

- RC flat slab
- RC beam & slab
- RC banded slab
- RC troughed slab
- PT Flat slab
- Composite slab & steel beam
- Composite slab & cellular beam
- Precast planks & steel Beam
- Precast planks & slimdek

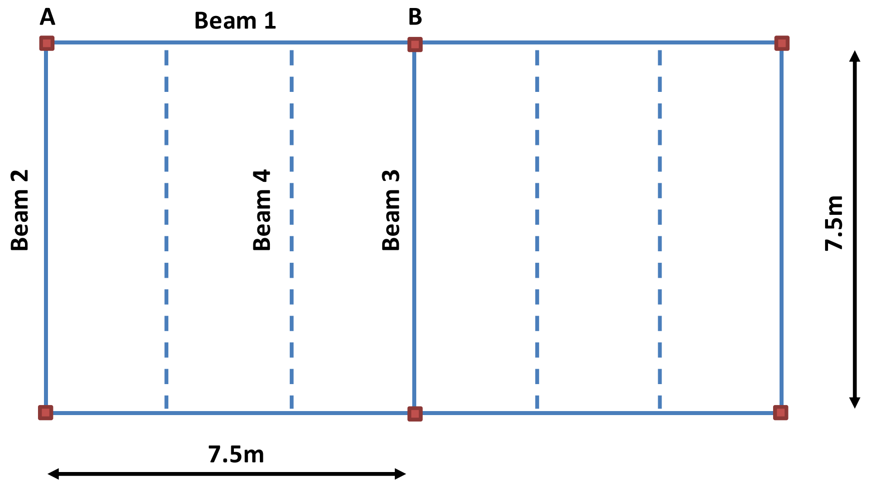

Fig 5 Floor plan used for Cundall embodied carbon assessment

To estimate the impact on the foundation design of steel and concrete framing the following assumptions were made:

- 4 storey building with storey height of 4 m.
- Façade load of 1.5 kN/m^2.
- Slab-on-ground for ground floor.
- Roof load of 1.5 kN/m^2.
- Allowable foundation bearing pressure of 250 kPa.

Table 6 shows the ECO_2 factors from ICE v2 that were used in the assessment.

		Embodied carbon factors ($kgCO_2$/unit)		
	Unit	Typical	Low	High
RC 20/25	kg	0.107	0.077	0.122
RC 25/30	kg	0.113	0.081	0.13
RC 28/35	kg	0.12	0.088	0.138
RC 32/40	kg	0.132	0.1	0.152
RC 40/50	kg	0.151	0.115	0.174
Precast	kg	0.18	0.144	0.203
Reinforcement	kg	0.077	0.077	0.077
Steel - hot rolled	kg	1.53	1	2.12
Steel decking	kg	1.53	1	2.12
Shear stud	per stud	0.4	0.3	0.6

Table 6 **ECO_2 emission factors used in Cundall study (from ICE v2 database)**

The embodied carbon of the pad footings was divided by 4 and added to the floor slab embodied carbon to ensure a fair comparison between the options. Table 7 summarises the results of the assessment.

Option	Frame	Formwork	Footing	Total	Low	High
RC flat slab	108	6	17	**131**	97	155
RC beam & slab	99	6	16	**121**	90	143
RC banded slab	102	6	16	**125**	93	147
RC troughed slab	106	6	16	**128**	95	152
PT flat slab	88	6	15	**108**	82	126
Composite slab & steel beam	111	0	10	**121**	83	158
Composite slab & cellular beam	105	0	10	**115**	78	151
Precast planks & steel beam	95	0	8	**103**	75	126
Precast planks & slimdek	136	0	8	**144**	102	183

Table 7 **Embodied carbon of footings and superstructure for different steel and concrete floor options**

Figure 6 shows the embodied carbon breakdown by material (steel, concrete and formwork) and Figure 7 shows the breakdown by element (slab, beams, columns and footings). Figure 8 shows the range in embodied carbon results using the low and high embodied carbon factors. An example calculation for the RC Flat Slab is shown in Figure 9.

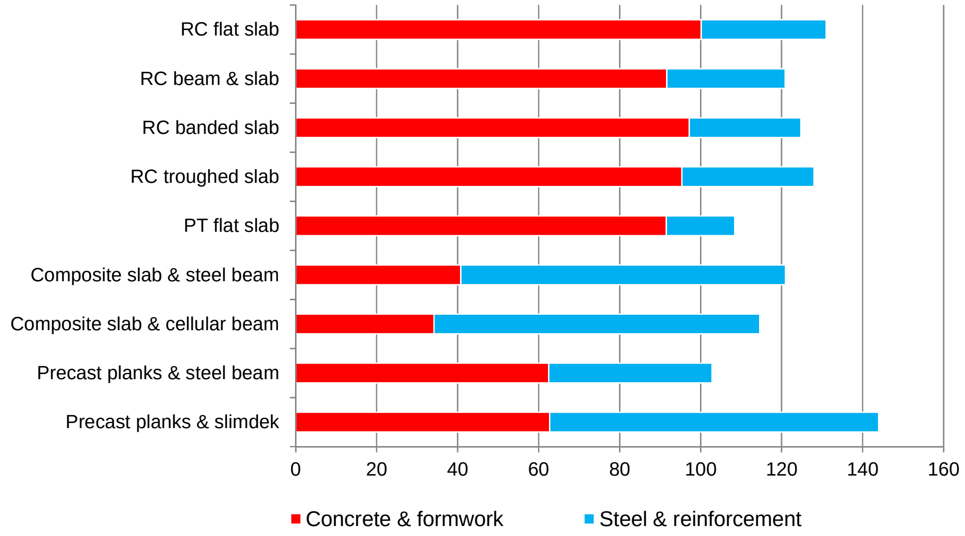

Fig 6 **Embodied carbon breakdown by material (kgCO_2e/m^2)**

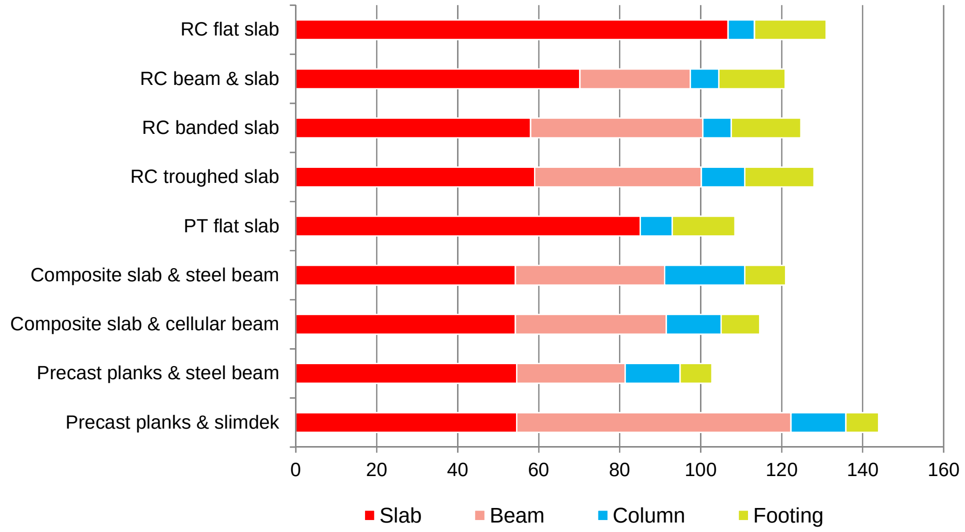

Fig 7 **Embodied carbon breakdown by element (kgCO_2e/m^2)**

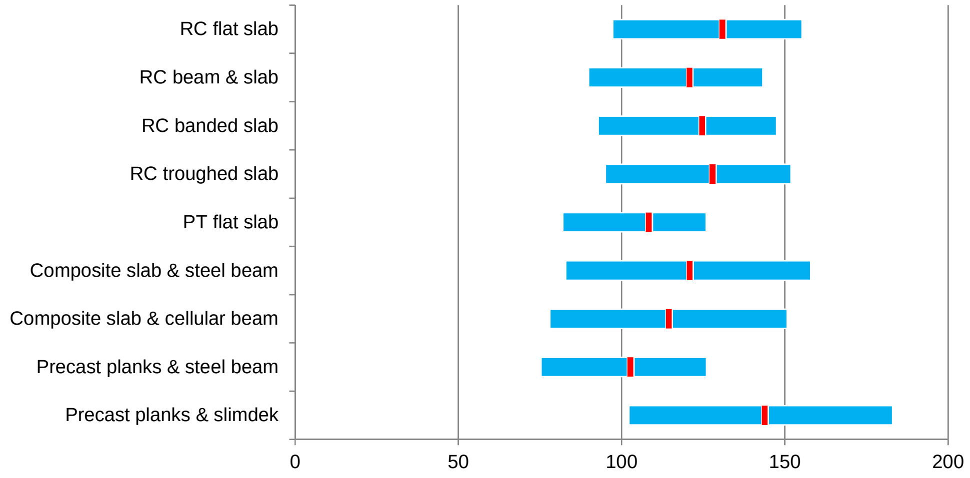

Fig 8 **Range in embodied carbon values (kgCO_2e/m^2)**

Structural Form:	RC Flat Slab				
Span:	7.5	m		Width	7.5
Live Load	5	kN/m2		Area	56
Slab Type:					

	Material	Grade	No. of	Depth (excl slab) (m)	Concrete volume Width (m)	Length (m)	Volume (m3)	Weight (t)	Reinf (kg/m3)	Reinf Weight (t)	Steel Weight Weight (kg/m)	Weight (t)	No. of studs per m	No. of studs	Typical tCO2 Concrete	Reinf	Steel	Shear Stud
Slab	Concrete	RC 28/35		0.275	7.5	7.5	15	37	110	1.7					4.4	1.3		
Beam 1	Concrete	RC 28/35		0		7.5	0	0		0.0		0.0		0	0.0	0.0	0.0	
Beam 2	Concrete	RC 28/35		0			0	0		0.0		0.0		0	0.0	0.0	0.0	
Beam 3				0			0	0		0.0		0.0		0	0.0	0.0	0.0	
Beam 4				0			0	0		0.0		0.0		0	0.0	0.0	0.0	
Col A	Concrete	RC 28/35		0.35	0.35	4	0	1	130	0.1		0.0			0.1	0.0	0.0	
Col B	Concrete	RC 28/35		0.4	0.4	4	1	2	285	0.2		0.0			0.2	0.1	0.0	
Footing A	Concrete	RC 20/25		0.63	2.5	2.5	4	10	100	0.4					1.0	0.3		
Footing B	Concrete	RC 20/25		0.98	3.9	3.9	15	36	100	1.5					3.8	1.2		
TOTAL FOR ALL FLOORS	**4**						**86**	**205**		**10**		**0.0**		**0.0**	**23.8**	**7.5**	**0.0**	**0.0**
													Total for 2 bays per floor		*43.0*	*13.2*	*0.0*	*0.0*
														kgCO2/m2	**95.6**	**29.4**	**0.0**	**0.0**

	Col A	Col B	*Total 2 bays*	
Weight of one floor & column	18	46	*82*	*82*
SDL + LL	16	42	*73.1*	*73.1*
Weight of all floors	133	354		
Weight of roof	12	32	*56.3*	*56.3*
Façade load	15	0		
Foundation load	**160**	**386**		
Area required	6	15		
Load distribution	0.85	1.15		
Note				
Simple support	*1*	*1*		
Continuous Beam	*0.85*	*1.15*		

	Typ	Low	High	Typ	Low	High
Slab	101.8	74.4	121.4	81%	82%	81%
Beam	0.0	0.0	0.0	0%	0%	0%
Col	6.2	4.5	7.5	5%	5%	5%
Footing	16.9	12.3	20.3	14%	14%	14%
Total	**125.0**	**91.3**	**149.2**			
check	*125.0*	*91.3*	*149.2*			
Concrete	95.6	70.7	111.0	76%	77%	74%
Steel	29.4	20.6	38.2	24%	23%	26%
Total	**125.0**	**91.3**	**149.2**			
formwork	6					

Fig 9 **Example calculation for flat slab**

2. TRADE ORGANISATION VIEWS

The claims by various organisations mentioned in Chapter 7 are based on sources shown in Table 8.

Claim	Source & commentary
Steel is lower than concrete and can also be lower than timber.	*'While people won't be shocked to learn that steel has less embodied carbon than reinforced concrete in comparable structural situations, they might be surprised to hear that the steel frame in the retail building study had less embodied carbon than the timber alternative.'* Source: Target Zero - Cost Effective Routes to Carbon Reduction, published by British Steel Constructional Steelwork Association and Tata Steel, May 2011. Note: This was based on the assumption that 99% of steel sections and purlins are recycled and 80% of timber goes to landfill where it produces methane. Refer to Appendix J for updated timber figures showing that only 30% now goes to landfill in the UK.
Timber is by far the lowest carbon material.	*'For all building types that have been assessed as part of this study, GHG emissions associated with the embodied energy of construction materials are lower if the timber content is increased. This study has demonstrated that, indicatively, it is possible to achieve up to an 86% reduction in GHG emissions by increasing the amount of timber specified in buildings.'* Source: Forestry Commission Scotland Greenhouse Gas Emissions Comparison Carbon benefits of Timber in Construction, a report by ECCM, August 2006 Refer to Section J7 of Appendix J for further discussion on accounting for carbon sequestration of timber.
Differences between concrete and steel are quite small and insignificant when compared to operational CO_2.	*'The embodied CO_2 of concrete is often thought to be much higher than other construction materials, when, in reality, the difference is typically quite small, and becomes insignificant when compared to, for example, a building's operational CO_2 emissions.'* Source: Concrete Centre website accessed 20 May 2011 A study by Arup for the Concrete Centre in 2010 concluded, for typical medium rise office, hospital and school buildings that *'concrete framed buildings have no more, and arguably slightly less, embodied CO_2 than a steel framed building.'* Source: Embodied CO_2 of Structural Frames by Sarah Kaethner and Jenny Burridge, The Structural Engineer, May 2012. The choice of superstructure (steel or concrete) supporting the floor structure '*makes very little difference to the overall impacts of the building.*' Source: The Green Guide to Specification, 3rd Edition, by Anderson, Shiers and Sinclair, published by Blackwell Publishing, 2002.

Table 8 Summary of various statements on embodied carbon of steel, concrete and timber framed structures

Notes

All websites were accessed on 15 June 2013 unless noted otherwise.

1. *Embodied CO_2 of Structural Frames* by Sarah Kaethner (Arup) and Jenny Burridge (The Concrete Centre), The Structural Engineer, May 2012. Refer also www.concretecentre.com/PDF/CQsummer2010.pdf.

2. *Embodied Carbon: The Inventory of Carbon and Energy* (ICE), by M. G. Hammond and C. Jones, BSRIA Guide BG10/2011.

3. As part of the Target Zero programme, the embodied carbon impact of five steel framed buildings and alternative structural options was measured using the life-cycle assessment (LCA) model CLEAR. The programme was sponsored by Tata Steel and the British Constructional Steelwork Association Ltd. www.steelconstruction.info/Target_Zero

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