Structural Applications of Ferritic Stainless Steels (SAFSS)
Work Package 3.4

Shear connection tests

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EXECUTIVE SUMMARY

This report details the methodology, results and analysis of 8 push tests performed at Brunel University in 2013 as part of the SAFSS project. These 8 tests break down into three groups as follows:

Test Series 1	Tests on 2 specimens where the shear studs are thru-deck welded through flat ferritic steel plate to the steel beam. The steel plate is to have the same material properties as the ferritic stainless steel Cofraplus 60 decking.
Test Series 2	Tests on 3 specimens where the shear connectors are thru-deck welded through the Cofraplus 60 ferritic stainless steel decking. This will require the stiffener in the trough to be "flattened out" in areas where shear studs are thru-deck welded to the steel Tee sections.
Test Series 3	Tests on 3 specimens where the shear connectors are welded directly to the steel section (not thru-deck welded). The ferritic stainless steel Cofraplus 60 decking profile will have pre-punched holes to allow placement over the shear connectors which have previously been directly welded to the steel Tee section.

The analysis of these tests allowed characteristic resistance to be determined for headed shear stud connectors and comparisons to be drawn between the experimental values and Eurocode guidance.

1. Introduction

This report describes the background, methodology, results and analysis from an investigation into the shear connection performance of composite slabs using ferritic stainless steel decking. This work has been conducted as part of the SAFSS (Structural Applications of Ferritic Stainless Steel) project, which is funded by the Research Fund for Coal and Steel (RFCS) and various industrial partners. The project is broken down into 9 different work packages of which work package 3 (WP3) is concerned with steel-concrete composite floor systems. Task 3.4 within this work package deal with the shear connection between the steel beam and the composite slab. Other tasks within this work package (not relevant to the current report) include tests on the decks and composite slab tests (i.e. in flexure), analysis of the heat transfer parameters for composite slabs as well as the fire performance; these are reported elsewhere (Real *et al*., 2011; Real *et al*., 2013; Lucey, 2011a; Lucey, 2011b; Faivre, 2012).

Clearly, the shear connection between the steel beam and the concrete slab is influenced by a number of factors, including whether the shear studs are through-deck welded or directly welded to the steel beam. Assessing the shear connection for this task has been essentially broken down into three main parts, each of which will be discussed in the current report:

1. Assessment of the welding technique and practicality of this process;
2. Push-out tests in order to determine the resistance of the shear connectors; and
3. Comparison of the results with design to EN 1994-1-1 (2004).

The layout of this report is as follows:

Section 2	Provides some background and context to the push tests, including a summary of ferritic stainless steel properties;
Section 3	Describes the welding trials using ferritic stainless steel decking.
Section 4	Defines the push test programme including the materials used and the procedures adopted;
Section 5	Presents and discusses the test results;
Section 6	Compares the test results with the Eurocode predictions; and finally
Section 7	Summarises the findings and conclusions.

2. Background

This section provides the context and background for the composite tests, firstly discussing composite construction, followed by methods of assessing the composite action and also the Eurocode design approach. Finally, the most relevant properties of ferritic stainless are summarised.

2.1 Composite construction

Steel-concrete composite construction is a popular choice amongst engineers and designers as it represents a very efficient use of materials, providing quick, cost effective and sustainable construction (Simms and Hughes, 2011). Typical ingredients include steel decking, slab reinforcement, shear connectors, structural steel section and the concrete slab, as shown in Figure 1. Composite behaviour occurs when the concrete slab, steel beam and profiled sheeting act as a unit. It consists of two main actions: (i) the concrete in the floor slab acting compositely with the profiled sheeting, and (ii) the steel beams acting compositely with the floor slab. In composite structures, the applied loads are transferred between the floor slab and the beams through shear connectors which are embedded in the concrete slab and welded to the steel beam. The use of steel-concrete composite floor slabs is well established and the design approach is presented in Eurocode 4 (EN 1994-1-1, 2004). It is estimated that the European market size for decking in composite floor systems is 60-80,000 tonnes per annum.

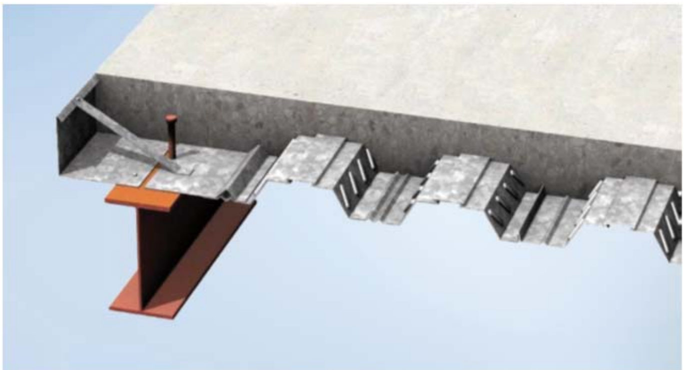


Figure 1 *Steel-concrete composite construction*

2.2 Assessment of composite behaviour

Historically, composite performance has been established using small-scale push test specimens, where a small number of shear studs are embedded in a concrete section and welded to a steel section which is then loaded whilst the concrete section is held in position. This type of test is described in Eurocode 4 (2004) and the essence of the test has remained unchanged since the 1930's (Hicks, 2007). Push tests were specified in the SAFSS Technical Annex (Form 1).

It is important to note that the validity of these tests has come into question in recent years as comparisons have shown that that the specimens have lower resistances and ductility than composite beams with the same material properties, cross-section and decking geometry (e.g. Rambo-Roddenberry, 2002; Bradford *et al*., 2006; Hicks, 2007). The reason for this lies in the loading and restraint conditions of the push tests, which are different to those experienced in a composite beam. In particular, the vertical forces and negative bending in the slab at the line of the shear connectors are currently ignored.

Nevertheless, a cost-effective and straight-forward alternative to the standard push test has yet to be developed and introduced in design guidance and therefore the tests adopted in this programme are as specified in Eurocode 4, and in accordance with the SAFSS Technical Annex. It is acknowledged that the push tests may not give the full impression of the composite performance but they can still give a useful insight into the most salient parameters and provide a basis for comparison with other materials. A primary objective of this study is to gain an insight into the effect of different shear connection arrangements on the composite performance.

2.3 Composite behaviour in the Eurocodes

Eurocode 4 (EN 1994-1-1, 2004) provides theoretical models for predicting the shear resistance of the shear connectors, i.e. their ability to transfer forces between the steel and the concrete. The models are presented in Sections 6.6.3.1 and 6.6.4.2 of the code. It is noteworthy that the rules in the

Eurocode were proposed for galvanised steel decking, and the aim of the current work is to investigate if the same rules can be applied to slabs using ferritic stainless steel decking. When stud connectors are welded within ribs of profiled steel decking, their resistance is reduced compared with their resistance in a solid slab. To account for this, Eurocode 4 applies an empirically-derived reduction factor (k_t) which is multiplied to the design resistance for a shear stud in a solid slab (P_{Rd}) to give the final shear stud resistance (referred to as $P_{Rd,rib}$ hereafter). $P_{Rd,rib}$ is defined in Equation (1):

$$P_{Rd.rib} = k_t P_{Rd} \tag{1}$$

It is noteworthy that Eurocode 4 provides no guidance as to how the standard solid slab specimen should be adjusted when decking is present, which has given rise to a large degree of scatter in test results (Hicks, 2007).

The reduction factor k_t is defined as:

$$k_t = \frac{0.7}{\sqrt{n_r}} \frac{b_0}{h_p} \left(\frac{h_{sc}}{h_p} - 1 \right) \text{ but } k_t \leq 0.85 \text{ for studs welded through profiled steel sheeting and } k_t \leq 0.75 \text{ for profiled sheeting with holes} \tag{2}$$

where:

b_0 = the width of a trapezoidal rib at mid-height of the profile;

n_r = is the number of stud connectors in one rib at a beam intersection,

h_p = the height of the steel sheeting measured to the shoulder of the profile;

h_{sc} = the as-welded height of the stud, but not greater than h_p + 75 mm.

P_{Rd} is defined as being the lesser of two values calculated using Equation (6.18) and (6.19) in Eurocode 4 for steel and concrete failure, respectively. Equation (6.18) determines the resistance based on the strength of the steel, presented here as Equation (3):

$$P_{Rd} = \frac{0.8 f_u \pi d^2 / 4}{\gamma_V} \tag{3}$$

where:

f_u the specified ultimate tensile strength of the material of the stud but not greater than 450 N/mm^2 for a profiled slab;

d the diameter of the shear connectors;

γ_V the partial factor.

Equation (6.19) in Eurocode 4 determines the resistance based on the strength of the concrete, presented here as Equation (4):

$$P_{Rd} = \frac{0.29 \alpha d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_V} \tag{4}$$

where:

α a function of the dimensions of the deck and shear connectors;

f_{ck} the characteristic cylinder strength of the concrete;

E_{cm} the secant modulus of elasticity of the concrete.

Annex B in Eurocode 4 states that the characteristic slip capacity δ_{uk} should be taken as the maximum slip capacity of a specimen δ_u reduced by 10%, where δ_u is the slip corresponding to the characteristic load level (P_{Rk}). In Clause 6.6.1.1(5) of that standard, a shear connector is defined as ductile if the characteristic slip capacity is at least 6 mm, and the minimum degree of shear connection rules in the standard are calibrated for this ductility.

2.4 Ferritic stainless steel in composite construction

The aim of this work package is to investigate the composite performance in structures using ferritic stainless steel rather than the more usual galvanised steel decks. Ferritic stainless steels do not contain significant quantities of nickel and are therefore cheaper and relatively price-stable compared with austenitic stainless steels. Ferritics also differ from the more commonly-used austenitic stainless steels in that they have higher mechanical strengths (approximately 250-330 N/mm^2 0.2% proof strength), are magnetic, have lower thermal expansion, higher thermal conductivity and are easier to cut and work.

The mechanical and physical properties of ferritics make them suitable for use in composite floor slabs where an attractive metallic surface finish is desirable. Unlike galvanised steel, ferritic stainless steels have a naturally occurring corrosion resistant surface layer so there is no requirement for applying protective surface layers and no remedial work or corrosion risk at cut edges in most normal applications. Furthermore, ferritics are easy to recycle compared to galvanised steel where the zinc from the galvanised coating must be removed prior to re-melting the steel.

Three of the 'traditional' ferritic grades are covered in the American SEI/AISI Specification for design of cold-formed stainless steel structural members (SEI/AISI, 2002) for thicknesses up to 3.8 mm. The South African (South African Bureau of Standards, 1997) and Australian/New Zealand (Standards Australia Standards New Zealand, 2001) structural stainless steel standards take similar approaches. The Eurocode for structural stainless steel, EN 1993-1-4 (2006) states it is applicable to three traditional ferritic grades (grades 1.4003, 1.4016 and 1.4512), however, the guidance is almost exclusively derived from work on austenitic and duplex stainless steels and in many cases ferritic-specific guidance is missing. EN 1993-1-4 refers to a number of clauses in other parts of Eurocode 3 such as EN 1993-1-2 (2005), 1-8 (2005), 1-9 (2005) and 1-10 (2005) which have not been validated for ferritic stainless steels. One exception is that EN 1993-1-2 (2005) includes data on one ferritic grade.

Despite the popularity of composite construction, and the benefits offered by ferritic stainless steel, the use of these materials for the decking has not been explored in any great detail up until now. There are two distinct advantages of using ferritic stainless steel over galvanized steel in these applications, which may be favourable in certain circumstances:

1. Corrosion resistance – this may be important in applications with exposed decking or in other sensitive environmental conditions, e.g. during the construction stage, or in a car park.

2. Thermal capacity – it has been shown that the thermal mass in floor slabs can be used to regulate temperatures in the structure thereby reducing the need for additional cooling and heating measures (Barnard and Ogden, 2006; Kendrick and Wang, 2007). This is optimized by using profiled slabs as the exposed area is greater than in flat slabs and also by having an exposed metal deck to allow good convective and radiative heating/cooling. Whilst the thermal performance of galvanised and stainless steel has not been shown to differ significantly, stainless steel is more likely to be exposed as it provides a more attractive appearance.

This section has provided a summary of composite behaviour including assessment and how it is dealt with in the Eurocodes as well as a general description of ferritic stainless steels. The following sections will discuss the tests that have been done to assess the composite performance of specimens using ferritic stainless steel decking, as well as comparing the data to the Eurocode 4 provisions.

3. Welding trials

The welded trials were an important pre-cursor to the composite push tests as shear studs have not been welded through ferritic sheeting for structural applications before. It is important to verify the practicality of the through-deck welding technique commonly used in the UK. The welding trials were completed at Hare Decking Ltd (formerly Richard Lees Steel Decking) in October 2012 within an open sided building and the weather conditions were fine. The studs were supplied by Nelson together with the appropriate type UF ceramic ferrule (for through-decking welding), in accordance with ISO 13918 (2008).

The connectors were 19 mm (diameter) ×100 mm (length) carbon steel shear studs which were welded through ferritic stainless steel sheeting to the structural steel beams using the same technique as used for regular galvanised steel decking (Figure 2). The sheeting was Grade 1.4003 ferritic stainless steel.

Figure 2 *Through-deck weldingtrial*

The studs were welded using the drawn arc process using a Nelson Nelweld 6000 converter (as shown in Figure 3) powered by a mobile generator with the specimen having an earth connection at each end to prevent arc blow.

Figure 3 *Nelweld 6000 convertor*

Once in position, each weld was visually inspected for an acceptable uniform 360° weld flash. In addition, they were subjected to the standard tests performed on welded shear studs in construction, i.e. the ring and bend tests (Figure 4); all welds passed these tests. Importance was given to subjecting the ferritic specimens to the same standard of testing as is commonly used on-site for galvanised decking.

Figure 4 *Steel-concrete composite construction*

Further observations from the trials were that the welds were very satisfactory and all welds were found to have good collars and to be of correct 'left after weld height', i.e. 95 mm 'left after weld height' for a shear stud which was originally 100 mm in height, as shown in Figure 4. Based on the results of these trials, it can be deduced that there is no greater risk using ferritic decking than using galvanised decking from the welding perspective. Once the welding trials were completed with satisfactory results, the push test specimens were prepared at the same location.

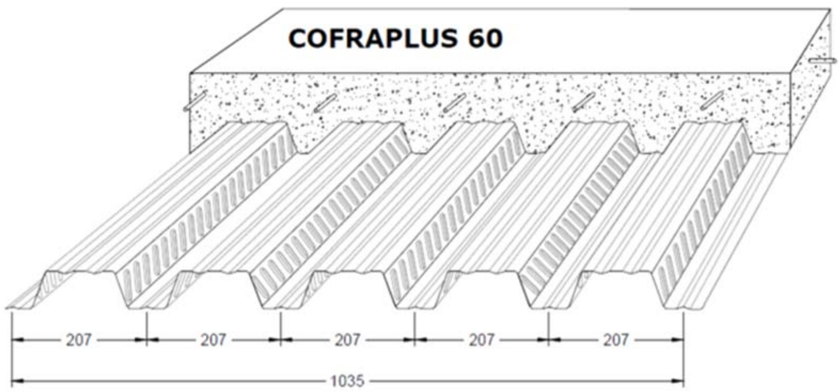
4. Experimental programme

The primary objective of the laboratory experiments was to gain a greater understanding of the composite performance of slab specimens using ferritic stainless steel decking by completing a series of standard push tests. A number of parameters can affect the load-slip characteristics between the steel and the concrete, such as the way that the stud is welded to the steel section, continuity of the decking and the strength of the concrete. The focus in these tests is to ensure that the composite performance of specimens using ferritic decking is, at least, as good as that when galvanised decking is used and also to investigate the effect of different construction arrangements.

Towards this end, a total of 8 push tests have been completed in the structures laboratory at Brunel University, in accordance with the SAFSS Technical Annex. As with other tasks in this work package (i.e. decking tests, composite slab tests), these tests have experienced delays owing to the deck rolling issues at Arcelor Mittal but, nevertheless, were completed in spring 2013.

4.1 Specimen preparation

All of the specimens used Arcelor Mittal Cofraplus 60 sheeting with a thickness of 0.8 mm in grade 1.4003 ferritic stainless steel (see Figure 5). The tests were completed in accordance with Annex B of Eurocode 4 (EN 1994-1-1, 2004), differing slightly in that the code describes a flat concrete slab without steel decking whereas the test specimens were profiled with ferritic stainless steel sheeting.



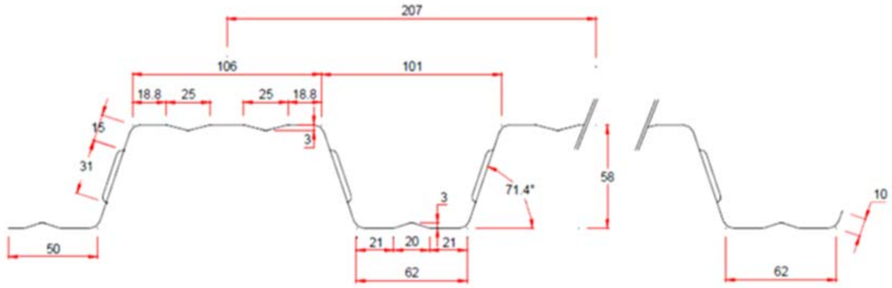


Figure 5 *Cofraplus 60 decking*

The shear studs were welded at Hare Decking Ltd., using the technique verified during the welding trial. Figure 6 illustrates a sample of sheeting with the studs welded through the deck into the steel beam.

Figure 6 *Specimen with studs welded through the ferritic sheeting*

Structural tees were used rather than universal column sections to enable both sides of the specimen to be cast at the same time, thus ensuring consistent concrete properties within each specimen. The general construction of the test specimens is shown in Figure 7. Anti-cracking mesh (A193) was included in each specimen as shown in the diagram. There were 2 shear studs in each individual slab for all tests, thus resulting in 4 shear studs per test.

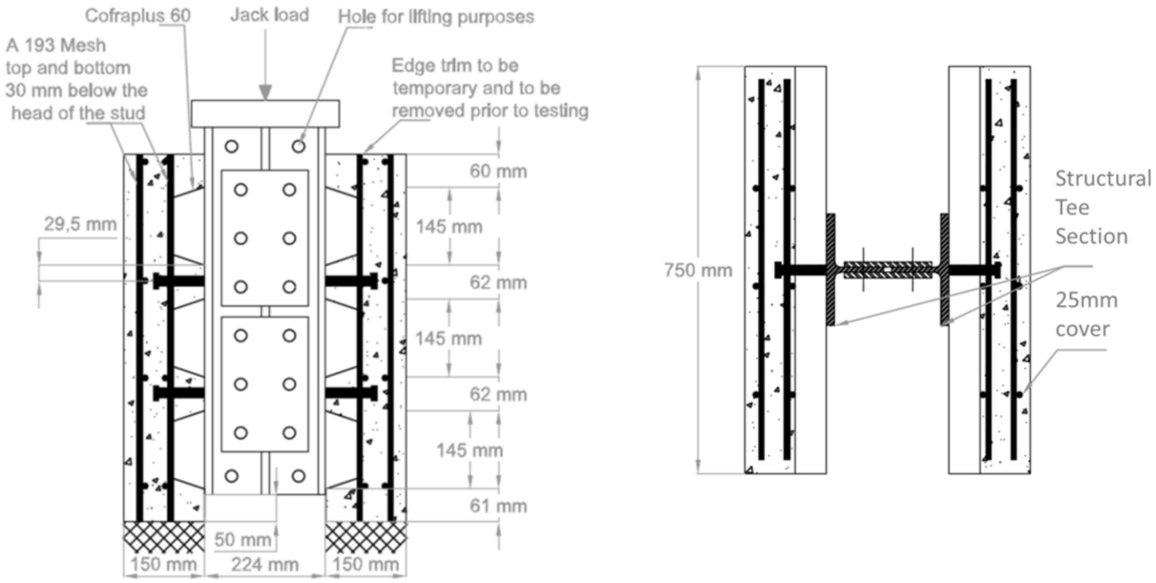


Figure 7 *Test specimen*

The specimens were prepared at Brunel University in the civil engineering laboratory, in accordance with EN 1994-1-1 Annex B, Section B.2.3. Owing to space restrictions, only one specimen (i.e. two slabs for a single test) was prepared from each batch. The moulds were prepared using timber-shuttering, which was designed to allow the steel beam to sit underneath it and for the profiled sheeting to be able to fit snugly into it. It was required to be sturdy and capable of bearing the forces created by the wet concrete, in addition to the weight and force of the vibration equipment. The joints in the formwork were taped and sufficiently tight to prevent any leaking during vibration and curing. Figure 8 shows the batching of materials for the concrete as well as the concrete being mixed.

Figure 8 *Concrete preparation*

The as-weld height of the shear studs was measured before casting. Figure 9 shows the preparation of the slabs, which were all air-cured. A total of 10 cylinders were cast from each batch which were then tested at 2×7 days, 2×14 days, 2×21 days, 2×28 days and 2× test day.

Figure 9 *Concrete being cast and finished slabs*

4.2 Test materials

Shear studs

The shear studs were welded at William Hare Decking Limited, following the welding trials. Nelson shear studs were used which were 19mm in diameter and 105mm in length. The yield strength of the shear studs (as per the delivery form from Nelson) was 446 N/mm^2 whilst the tensile strength was 488 N/mm^2. The elongation at failure was 16.2%.

Steel sections

The tee sections (UKT Split from Advance® UKC) were made from S355 steel and the size used was 203×102×30 kg/m in all cases.

Ferritic stainless steel decking

The ferritic stainless steel profiles were rolled at the Arcelor Mittal facility in Strasbourg to the Cofraplus 60 specifications. They are made from Grade 1.4003 ferritic stainless steel in a 2B finish, and are 0.8mm thick. Figure 5 presents the dimensions of the Cofraplus 60 decking, in accordance with the brochure. The yield strength of the decking material was 326 N/mm^2 and the ultimate strength was 480 N/mm^2.

Reinforcing mesh

Anti-cracking meshing (A193) was used in all specimens, in accordance with the test specification. The A193 mesh was cut to size in order for it to fit into the formwork easily.

Concrete

Normal weight concrete Grade C30/37 was used. The concrete mix had a 1.5 : 1.5 : 1 (aggregate : sand : cement) ratio.

4.3 Test programme

It was originally planned to conduct 8 push-out tests, 4 with single shear studs and 4 with double shear studs, in accordance with the Technical Annex. However, upon receipt of the ferritic decking from Aperam (formerly Arcelor Mittal), it was noted that the sheets had a stiffening rib in the trough, where the shear stud would be through-deck welded. It was not known if the presence of this rib during the welding process might lead to contamination of the weld. As a consequence, a revised plan for the 8 push-out tests was devised to determine the shear capacity of through-deck welded studs with stainless steel decking:

Test Series 1 Tests on 2 specimens where the shear studs were through-deck welded through flat ferritic steel plate to the steel beam. The steel plate had the same material properties as the ferritic stainless steel Cofraplus 60 decking as it was from the same coil. These test specimens are called 1-A and 1-B, and were identical.

Test Series 2 Tests on 3 identical specimens where the shear connectors were through-deck welded through the Cofraplus 60 ferritic stainless steel decking. The decking was rolled with a central stiffener in the centre of the trough which had to be hammered flat local to the stud position in the through-deck welded specimens to ensure direct electrical contact through the components as well as the integrity of a homogeneous weld. These test specimens are called 2-A, 2-B and 2-C.

Test Series 3 Tests on 3 identical specimens where the shear connectors were welded directly to the steel section (not through-deck welded). The ferritic stainless steel Cofraplus 60 decking profile had pre-punched holes to allow placement over the shear connectors which have previously been directly welded to the steel tee section. These test specimens are called 3-A, 3-B and 3-C.

Whilst through-deck welding is popular in the UK, other parts of Europe typically use studs welded directly to the steel beam and decking with pre-punched holes, which is why it was important to look at both of these scenarios. In order to ensure that the flattening process did not affect the integrity of the weld, two tests (1-A and 1-B) had though-deck welded shear studs but welded through a narrow strip of flat ferritic stainless steel sheeting with the same material properties as the profiled sheeting. A profiled sheet with pre-punched holes was then placed over the studs. All concrete slabs had the same profile and hence an identical volume of concrete. The test programme is summarised in Table 4.1.

Table 4.1 - Push-out test programme

Series:	Number of tests:	Details	Shape of slab	Continuity of deck beyond weld?	Through-deck welded?
1	2	Studs welded through narrow flat sheet	Profiled	No	Yes
2	3	Studs welded through continuous profiled deck	Profiled	Yes	Yes
3	3	No through-deck welding	Profiled	No	No

4.4 Testing

The compressive strength of the concrete was determined by crushing cylinders at 7 days (following casting), 14 days, 21 days, 28 days and also on the day of testing. The results are presented in Table 4.2.

Table 4.2 – Concrete strength data

Cast No.	**Specimen Name**	**Date of Cast**	**Age at day of testing (days)**	**Average 7 day strength (N/mm^2)**	**Average 14 day strength (N/mm^2)**	**Average 21 day strength (N/mm^2)**	**Average 28 day strength (N/mm^2)**	**Average test day strength (N/mm^2)**
1	1-A	19.12.2012	162	**24.05**	28.89	33.10	37.05	35.82
2	1-B	10.01.2013	140	**28.41**	29.27	34.56	40.35	44.44
3	3-A	14.01.2013	120	**22.98**	29.76	34.16	38.52	37.54
4	3-B	17.01.2013	124	**25.40**	25.79	28.02	30.54	29.59
5	3-C	21.01.2013	128	**25.39**	26.65	30.22	34.21	39.25
6	2-A	24.01.2013	116	**26.03**	25.74	26.41	27.17	30.05
7	2-B	28.01.2013	115	**26.04**	26.73	26.97	27.12	41.26
8	2-C	31.01.2013	119	**26.63**	28.27	29.54	30.81	34.29

The push tests were completed in the structures laboratory at Brunel University during May 2013. The test frame is shown in Figure 10, with a specimen in position.

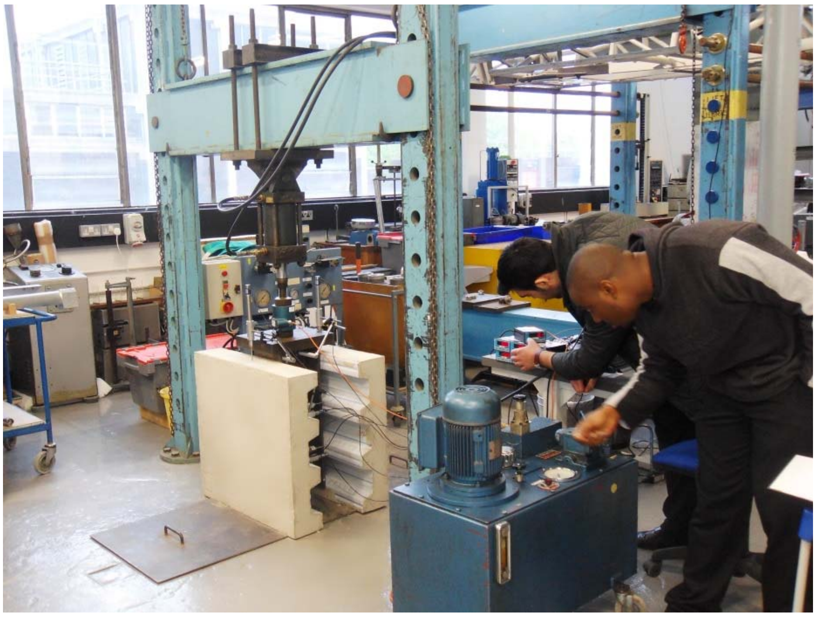


Figure 10 *Test frame at Brunel University*

In each case the test specimens were loaded to failure by applying a hydraulic jack to a plate on top of the steel tees. Load was transferred to the concrete through the shear studs. In accordance with EN 1994-1-1, the load was first applied in increments up to 40% of the expected failure load and then cycled 25 times between 5% and 40% of the expected failure load. In each test, following the cycles, the load and displacement were gradually increased until failure occurred, typically by concrete pull-out, which was accompanied by a significant reduction in load capacity. The longitudinal slip between each composite slab and the steel section was measured continuously using displacement transducers, as was the lateral displacement of the slabs.

4.5 Test results and observations

Load-slip relationships for Series 1, 2 and 3 are presented in Figures 11- 13 respectively whilst the Figure 14 shows a specimen after testing. A summary of all the experimental data is presented in Table 4.3, where f_{ck} refers to the compressive cylinder strength of the concrete on the day of testing (taken as the average of three cylinders), P_f is the failure load observed in the tests and P_{Rk} is the characteristic resistance per stud equal to 90% of P_f divided by the number studs (4 in this case), as defined in Eurocode 4 Annex B (EN 1994-1-1, 2004). δ_u is the slip corresponding to P_{Rk} whereas δ_{uk} is the characteristic slip equal to δ_u reduced by 10%. The yield (f_y) and ultimate (f_u) strengths of the ferritic decking were 326 N/mm^2 and 480 N/mm^2, respectively, based on taking the average of 4 tensile test coupons. On the other hand, the yield and ultimate strengths of the shear studs were 446 N/mm^2 and 488 N/mm^2, respectively.

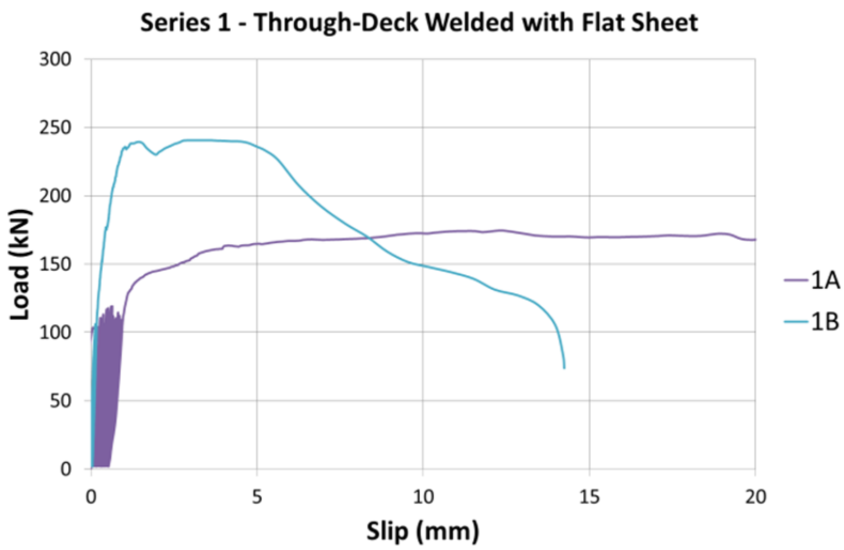


Figure 11 *Load-slip curves for Series 1*

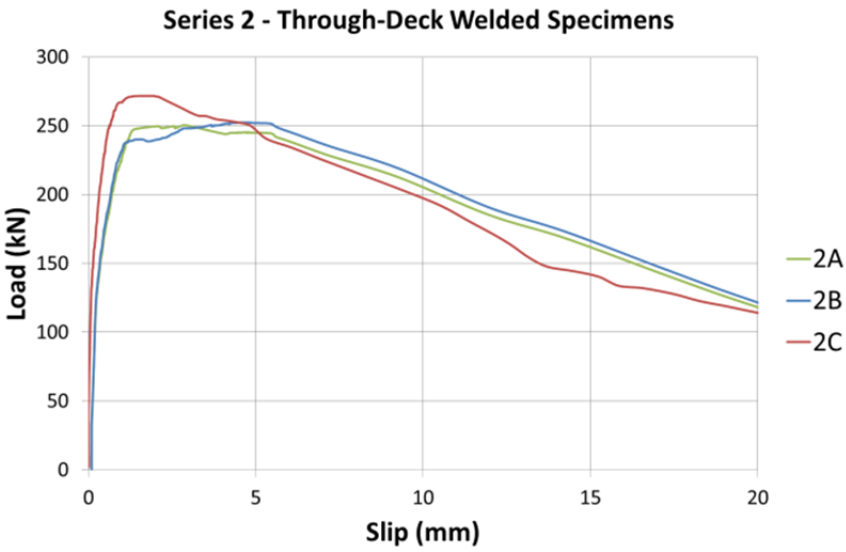


Figure 12 *Load-slip curves for Series 2*

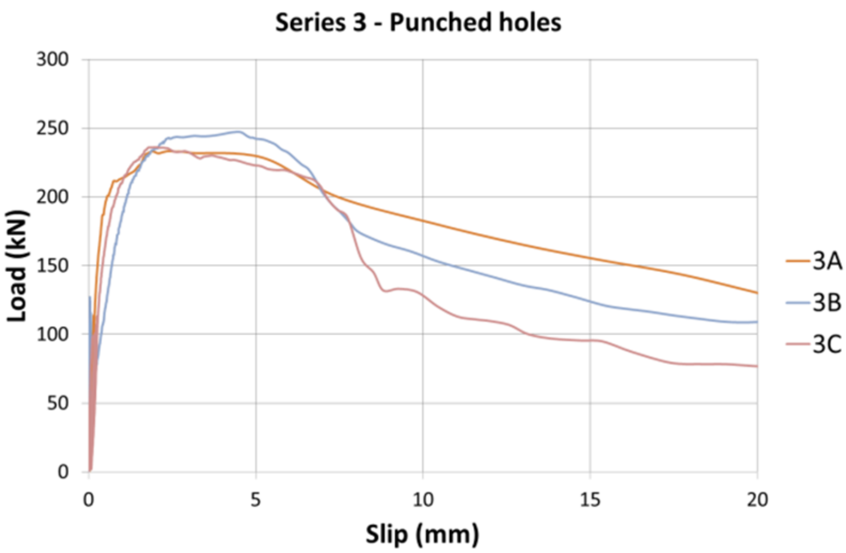


Figure 13 *Load-slip curves for Series 3*

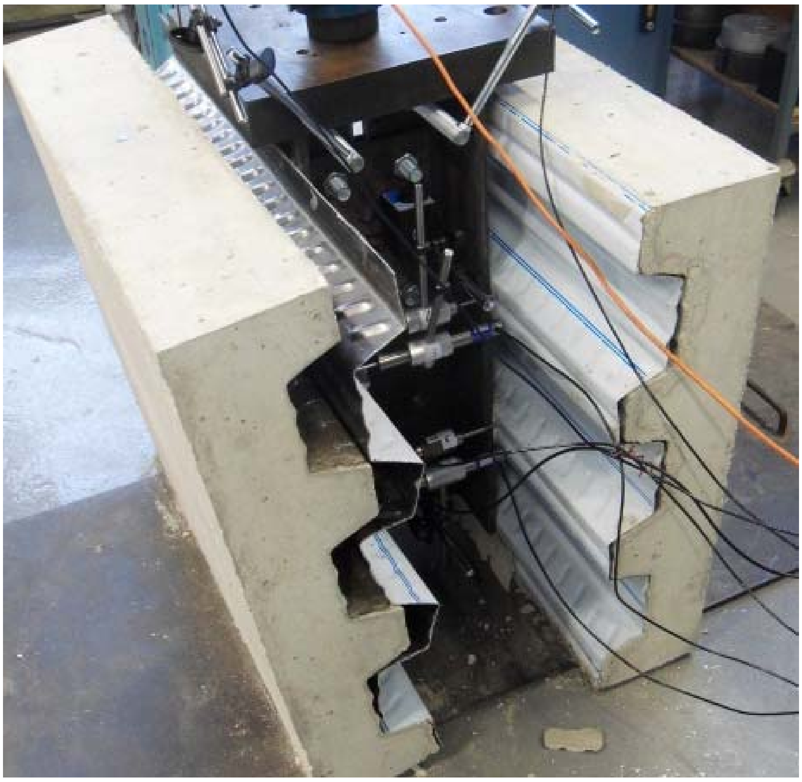


Figure 14 *Failed specimen after testing*

Table 4.3 – Results of push tests

Specimen	f_{ck} (N/mm^2)	$P_{f,total}$ (kN)	P_{Rk} (kN)	δ_u (mm)	δ_{uk} (mm)
1-A	35.82	174.66	43.66	22.07	19.86
1-B	44.44	234.70	58.68	6.43	5.78
2-A	30.05	249.72	62.43	7.67	6.90
2-B	41.26	245.19	61.30	9.62	8.66
2-C	34.29	270.93	67.73	5.61	5.05
3-A	37.54	231.66	57.92	6.77	6.09
3-B	29.59	244.20	61.05	6.58	5.92
3-C	39.25	232.40	58.10	6.87	6.18

During the 25 cycles between 5% and 40% of the expected failure load, the specimens remained in good condition with no visible cracks, although concrete movement could be heard. At about 80-90% of the peak load and a slip of around 1 mm, visible delamination occurred between the concrete slab and the decking. With the addition of more load, the concrete began to visibly and audibly crack. Failure was typically accompanied by a notable drop in the load-carrying capacity of the specimen.

All of the specimens demonstrated concrete pull-out failure around the shear connectors although one stud was found to have sheared off in Specimen 3-C. It is impossible to know exactly when this happened although it is likely that it was after the concrete had failed as the displacement increased.

After each test, the concrete slab was removed from the profiled sheeting, which was very easy as no bond remained. Figure 15 shows Specimen 3-A without the steel deck where the evidence of concrete pull-out can be seen, whereas the steel deck from this test is presented in Figure 16, showing the remaining concrete around the shear stud.

Figure 15 *Failed specimen – concrete*

Figure 16 *Failed specimen – decking*

Concrete pull-out failure occurs when the concrete surface fails due to tension occurring across the failure surface. It has been shown that standard push-tests are dominated by failure of the concrete around the shear connectors, as was observed in these tests, rather than shearing of the shear connector itself (Smith, 2009). The typical failure surface for single shear connectors is a cone of concrete starting underneath the head of the shear connector and growing in diameter down the length of the shear connector, although the shape is restricted by the shape of the decking (see Figure 16). However, this type of failure would be less likely to occur in a real composite member which is loaded in bending and, for this reason, many researchers have added a lateral load to the test specimens (e.g. Easterling *et al*., 1993; Rambo-Roddenberry, 2002; Bradford et al., 2006; Smith, 2009; Smith and Couchman, 2010).

5. Comparison with Eurocode values

The main aim of the composite push tests was to provide adequate data to enable the existing rules in Eurocode 4 (which are typically used for slabs using galvanised steel decking) to be verified for slabs using ferritic stainless steel sheeting. This section presents a comparison of the test results with the Eurocode design values.

Using the equations presented in Section 2.3, the reduction factor (k_t) for the Cofraplus 60 decks used in these tests is found to equal 0.63; k_t is defined in Equation (2). The design strength ($P_{Rd,rib}$), as defined in Equation (1), for each of the test specimens is presented in Table 5.1, together with the ratio of the test resistance to the design resistance. The ratio of $P_{Rk}/P_{Rd,rib}$ varied between 0.91 for Specimens 3-A and 3-C and 1.06 for Specimen 2-C. It is clear that this ratio is higher for Series 2 relative to Series 3 showing that the through-deck welded shear connectors offer slightly greater shear resistance. In general, given that the design resistance $P_{Rd,rib}$ values in Table 2 do not include safety (γ) factors, having a 'test to design' ratio of around 1 is as expected.

Table 5.1 – Comparison with the Eurocodes

Specimen	P_{Rk} (kN)	δ_{uk} (mm)	$P_{Rd,rib}$ (kN)	$P_{Rk}/P_{Rd,rib}$
1-A	43.66	19.86	64.07	0.69
1-B	58.68	5.78	64.07	0.92
2-A	62.43	6.90	64.07	0.98
2-B	61.30	8.66	64.07	0.96
2-C	67.73	5.05	64.07	1.06
3-A	57.92	6.09	64.07	0.91
3-B	61.05	5.92	64.07	0.96
3-C	58.10	6.18	64.07	0.91

The ductility of the specimens was reasonable with all of the δ_{uk} values being around the 6 mm value required by the Eurocode in order to justify the assumption of ideal plastic behaviour of the shear connection. As stated before, it has been shown that these types of push tests give lower strength and slip resistances than composite beam specimens. Hicks (2007) showed that studs in beam tests out-performed those in push tests both in terms of resistance and ductility, by 46% and 269% respectively.

In particular, it has been shown that push test specimens that fail by concrete pull-out, as occurred in these tests, give brittle failure and low strengths (Johnson and Yuan, 1998).

There is no data in the literature for equivalent tests using galvanised steel decks. However, Bradford *et al*. (2006) reported some tests which were conducted in a similar manner (i.e. no lateral force applied) and used galvanized decking with a very similar profile shape to the Cofraplus 60. These tests appeared to show very limited ductility (δ_{uk} values significantly below 6 mm) which the authors attributed to the test arrangement causing premature failure. A new test procedure was proposed wherein a normal force is applied to the specimen in addition to the longitudinal force in order to prevent concrete pull-out failure and unrealistically low ductility.

On this basis, it is reasonable to deduce that specimens with ferritic stainless steel decking behave at least as well as slabs with galvanised decking and therefore conform to the current requirements of the Eurocode specification.

6. Concluding remarks

This report has described the background, preparation, methodology, results and analysis from a series of push tests which were completed as part of the SAFSS project. This report is the deliverable for Task 3.4 in Work Package 3. An overview of the context in which these tests took place was first given, together with a brief summary of ferritic stainless steels, including their relevant properties for structural use. One potential application for ferritics is for decking in composite construction and, towards this end, a series of push tests were conducted in order to determine the suitability of these materials for this application.

The first task which was described was the welding trials, which examined the practicality of the through-deck welding technique for composite slabs using ferritic stainless steel decking. The trials were very successful with the outcome being that typical carbon steel shear studs can be welded through ferritic stainless steel decking without any issues; the performance was similar to that when galvanised decking is employed.

Following this discussion, the push tests were described including a detailed account of the preparation of the samples, the material properties of all the components, an assessment of the test results and also a comparison of the test data with the Eurocode 4 design rules. It was concluded that the resistance of shear connectors in the slabs using ferritic stainless steel decking is comparable with the resistance given in Eurocode 4 (EN 1994-1-1, 2004) when through-deck welded and when directly welded to the steel section through pre-cut holes in the deck. All of the tests failed in the same manner which was through concrete pull-out, regardless of the construction form used. The results also showed that there is sufficient ductility to use the current minimum shear connection rules in Eurocode 4 for headed stud shear connectors.

It is accepted that the method of testing is not ideal as it creates internal forces which are different to those that occur in composite members under bending forces. However, as a starting point, it is important to complete the tests in accordance with the Eurocode so that comparisons with existing design equations can be made.

6.1 Recommendations for future research

The work discussed this report provides a good basis for understanding the composite performance of slabs using ferritic stainless steel sheeting. The observations and results highlighted a number of issues and topics that would benefit from additional exploration and assessment in the future. There are summarised as:

- Conduct more tests with different arrangements to investigate the effect of:
    - staggered pairs of shear connectors;
    - positioning of shear connectors in favourable, central and unfavourable locations to determine the effect of the location on the resistance;
    - ‘favourable’ or ‘unfavourable’ placement of the connectors;
    - larger spacing between the connectors (on larger flanges);
    - weaker and stronger concrete for verification of the model; and
    - use a deck with different geometric properties.
- Further work is required in order to numerically analyse the push test specimens using FEA programs such as ABAQUS or Ansys so that the effect of the loading conditions can be quantified and further understood.
- In addition, given the shortcomings of the push test method reported in this report, it would be wise to conduct more composite beam tests in order to ensure that the Eurocode 4 rules are applicable for composite structures using ferritic stainless steel decking. For this reason, recommendations or modifications to the Eurocodes have not been proposed.
- It would also be useful to conduct identical tests using galvanised steel decking in order to enable a direct comparison to be made.

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