Advantages of composite construction

With regards to Civil and Structural Engineering, composite construction typically refers to the use of steel and concrete formed together so that the resulting component behaves as a single element. The aim of composite construction is to utilise the best properties of the different materials and to deliver performance that is greater than had the individual components been used together but not unified. In the case of steel and concrete, the best properties would be the tensile capacity of the steel and the compressive capacity of the concrete. (Nethercot, 2004)

Composite construction is an effective method of construction and delivers good performance. The methodology for designing composite structures has been researched in great detail. For these reasons, composite construction is a very popular method of construction around the world.

In order for the materials to behave as one element, it is necessary for some method of connecting the two materials. A shear connection between two materials will enable composite action between them. (The Institution of Structural Engineers)

2. 1. 1 Benefits of Composite Construction

The benefits of composite construction include speed of construction, performance and value. Steel framing for a structure can be erected quickly and the pre-fabricated steel floor decks can be put in place immediately. When cured, the concrete provides additional stiffness to the structure.

Additionally, the concrete encasement protects the steel from buckling, corrosion and fire. Service integration within the channels on the composite decks is another advantage to composite construction.

Building quality standards can be adhered to easily by the use of pre-fabricated decks. Excessive deflections can be controlled by cambering the beams or by shoring the metal decks to limit deflection when concrete is poured.

2. 1. 2 Codes for the Design of Composite Structures

The design of composite structures was governed by the British Standards.

BS 5950-3-1 dealt with the design of beams whilst slabs were governed by BS 5950-4. Pre-fabricated decking used with composite structures was governed by BS 5950-6.

Since the introduction of the Eurocode set of standards for the European Union, the design of composite structures is standardised by Eurocode 4. (BS EN 1994-1-2)

(BCSA; TATA Steel; Steel Construction Institute)

2. 1. 3 The Principle of Composite Action

The principle of Composite Action underpins the use of composite materials in construction. It relates to the interaction of two or more separate elements acting together and contributing together rather than separately. By physically connecting them, the strength of the beams and the resistance to bending, shear and torsion are significantly increased.

The Principle of Composite Action is best illustrated as an example. The diagrams below shows two uniform concrete beams placed on top of each other and loaded with a uniformly distributed load. Both beams will resist the load independently and there will be relative movement between them. The bending strength will be the sum of the individual beams contribution. If the beams have width w and height h, the bending strength M will be:

However, if the two beams are connected rigidly together by shear connectors and the relative movement between them is eliminated, the width remains w whilst the height becomes 2h. The bending strength M will be:

This represents a doubling of the bending strength through the use of composite action. This is the principle behind the use of steel beams with reinforced concrete floor decks. The two are connected by shear connectors. The increase in strength due to composite action can be as much as 20%, resulting in lighter and thinner sections. (TATA Steel)

Figure : The differences between identical beams when composite action is utilised. The beam on the left is comprised of two concrete beams that are not connected compositely. When loaded, there is relative slip between the beams. The component beams on the right are rigidly connected together by means of shear connectors. When loaded, there is no slip between the beams and the assemblage behaves as one large beam. Image from TATA Steel.

2. 2 Composite Floor Deck Slabs

Composite floor decks are comprised of either steel beams or concrete embedded steel beams together with a reinforced concrete slab. The profiled steel formwork that supports the concrete floor during casting is of vital importance as it also provides the shear bond to enable the materials to work compositely. The role that the profiled decking plays in fire resistance will be discussed in more detail in Section 3. 3. Composite action is achieved between the beams and slab by the use of shear connectors that will be discussed in Section 2. 4 in more detail. (Metal Cladding and Roofing Manufacturers Association, 2003)

The profiled steel decking used in the construction of composite floor systems contributes significantly to the ease and speed at which the structure is construction. It acts as both the permanent formwork and contributes to the overall requirement of reinforcement. The performance of the steel decking when exposed to fire needs careful consideration and is dealt with in Section 3. 2. Additional reinforcement is positioned in the troughs of the decking to ensure adequate performance in fire.

Benefits associated with using profiled steel decking are reduced dimensions and weight of the overall structure. They also provide satisfactory performance in the areas of strength and economic constraints during construction. (Michel Crisinel, 2004)

2. 2. 1 Types of Composite Slabs

The classification of composite slabs depends primarily on the geometry of the steel deck profile used. Shallow decks are classified by depths in the range of 120-200mm whilst deep decks are classified by depths in the range of 200-350mm. (Aida Rodera Garcia)

The most common composite slab consists of the profiled steel decking and concrete cast in-situ. Once cured the concrete and decking act compositely. Sufficient interaction between the concrete is achieved by a chemical bond and a mechanical bond facilitated by the shape of the decking. In design, it is common to neglect the contribution from the chemical bond as it is unreliable. There are many different types of profiled decking available and contribute to the classification of the slab. (Nawy, 2008)

Pre-cast concrete slabs can also be used to form a composite floor deck system. The slabs must be designed specifically so that they can interact with the beam system in place. The composite action in this case can be achieved by welded shear studs and transverse reinforcement across the floor deck. By utilising pre-cast concrete decks, hollow core slabs can be used. These can reduce the weight of the whole building whilst offering similar performance to solid slabs. Pre-Cast slabs are usually covered by a layer of concrete after installation to produce a more finished and aesthetic result.

Figure : Examples of Hollow-Core Slabs The final type of composite floor slab is the Slim Floor. This consists of the supporting steel beam being encased in the concrete with the lower flange of the beam supporting the floor. Diagrams depicting the various composite slab types in use today are shown below.

Figure 4: Proprietary Slim Floor System " Slimdek"- TATA Steel

Figure 3: Example of Solid Slab with Topping and Encasement cast In-Situ Proprietary Slim Floor System " Slimdek"- TATA Steel

http://ars. els-cdn. com/content/image/1-s2. 0-S0143974X99000759-gr5. gif

2. 2. 2 Design

Composite floor decks are comprised of permanent formworks of profiled steel decking. The decking serves to support the concrete during casting and before it has cured sufficiently to support itself. It is important to ensure that after curing sufficient interaction between the concrete and steel has developed so that the assembly behave compositely. The rebar is placed in the steel decking prior to pouring as is a steel mesh that serves to minimise cracking over supports and to increase the fire resistance of the floor deck. Most decks achieve a satisfactory degree of shear connection with the concrete by the presence of embossments and indentations along the profile of the decking. This type of shear connection is known as a shear bond. (Steel Construciton Institute, 1994)

The decking also contributes to the stabilisation of the structure against lateral torsional buckling of the steel supporting sections and transfers wind loading forces to the walls and columns. The decking also serves to minimise cracking of the concrete slab during expansion and contraction such as during curing and fire. This will be further discussed in Section 3. (Aida Rodera Garcia)

The steel decking is normally in the range of 0. 9-1. 5mm thick and has a yield strength of 280-350 N/mm2. Higher strength steels may be used if the spans are longer than the norm. Typical spans for a composite floor deck are between 2. 7 and 3. 6m although longer spans may be achieved by shoring the deck during construction. Galvanisation of the faces of the decking is done to prevent damage to the steel during pouring and in service.

2. 2. 2. 1 Concrete Type & Strength

Both Normal Weight Concrete (NWC) and Light Weight Concrete (LWC) may be used in composite floor slab construction. The most convenient method for concrete placement is by pump. The concrete type and grade is an important design consideration as it affects the final stiffness of the deck system and the strength of the shear connection.

2. 2. 2. 2 Steel Decking Resistance

The elastic moment resistance of the steel decking may be calculated from the effective breadth of the steel elements in compression. Stiffeners are present in the deck design and contribute to increasing the effectiveness of the section. In designing a deck system, moment redistribution is not allowed. This results in an underestimate of the critical load for the decking. (ECCS, 1993)

2. 2. 2. 3 Deflection

Deflection limits for a composite slab are generally the span/180. However, by shoring the composite slabs during casting, this can effectively be reduced to zero. Increased deflection limits of span/130 are allowed if pooling of the concrete occurs in the middle of the span after pouring. (ECCS, 1993)

2. 2. 2. 4 Transverse Reinforcement

The strength of the concrete should be checked to ensure it is capable of receiving the force transferred from the shear connectors. Where the concrete may be susceptible to cracking, the provision of transverse reinforcement perpendicular to the beam is required. (Aida Rodera Garcia)

2. 2. 3 Failure

The ultimate moment resistance of a composite slab is defined as the point at which less than 2mm of longitudinal slip has occurred between the concrete and the decking. Failure of a composite deck is deemed to have occurred when slip of more than 2mm occurs. Failure most commonly occurs during curing before the concrete has reached its design strength.

2. 2. 4 Fire Resistance of Composite Sections

The minimum slab depth will be determined by the fire insulation requirements and the amount of reinforcement that is necessary to withstand loading at the fire limit state. This will be dealt with in more detail in Chapter 3.

2. 3 Composite Beams

A composite beam can be structurally described as a T-Beam, with the top flange composed of concrete in compression and the steel section in tension. Forces between the two materials are transferred by shear connectors. The principle of composite action with regards to beams leads to increased strength and stiffness of the system whilst using a smaller steel section.

The two main variants of composite beams used today are shown in Figure 6. Beams are usually composed of a UKB or UKC section, partially or fully encased in concrete for strength and fire resistance purposes. (ECCS, 1993)

2. 3. 1 Design

In composite beam design, the steel section is first sized to adequately support all the loads acting on it. No contribution is taken into account from the concrete as it has not gained adequate strength for composite action. A common value for the load applied to the beam from the concrete slab is 0. 75kN/m2. Once the loading has been calculated, the beam is designed according to Eurocode 3. The presence of steel decking normal to the steel section provides lateral restraint to the beam. In this case, the beam can reach its full plastic moment.

In cases where the presence of steel decking is parallel to the beam, the beam is only laterally restrained at the connections at either end and the buckling resistance of the beam must be calculated based on its effective length.

The effective breadth of the concrete flange, taken from the supported slab, is approximated as the span/8 on both sides of the beam. This results in an effective breadth of span/4 for simply supported internal beams.

2. 4 Shear Connectors

Shear connectors are an essential element of composite construction if it is to perform adequately. The main purpose of the shear connector is to provide longitudinal shear resistance between the materials so that they act compositely and to facilitate the interaction between the different materials and to allow them to act as one. (MCRMA, 2003)

The shear connection between steel beams and concrete slabs is typically achieved by headed steel studs, welded to the top flange of the steel beam and subsequently encased in concrete. The performance of the studs depends on their dimensions and the spacing along the flange of the beam. Near supports, where the shear forces are greatest, the spacing is reduced. Shear studs can be welded through steel decking.

Welding shear studs to the steel beams has a number of limitations and guidelines. The flange of the steel beam has to be bare and can not contain any contaminants such as intumescient paint used as fire protection or moisture. This method also works best when the thickness of the steel decking is less than 1. 25mm. Weather conditions will also affect the use of this method of connection. Excess moisture in the air can result in the finished weld being brittle and prone to sudden failure. Shear connectors can also be placed during production although mistakes in placement can be difficult and costly to correct.

The purpose of a shear connector is to primarily resist lateral shear forces and displacement between the beam and concrete slab. However, they are also designed to prevent upward displacement of the slab from the beam as it has a tendency to do. For this reason, the studs are headed to provide vertical resistance to seperation.

2. 4. 1 Types of Shear Connectors

In the past, the most common method of shear connection was a headed stud. As welding is only suitable for decking with a minimum thickness, where the decking is too thin, nailed studs are used instead. The choice of which shear connector is used ultimately depends on the shear resistance required and the grade and strength of concrete used.

There are four main types of shear connector in use today. The most common is the headed stud. However, with the advent of thinner composite decks, the use of headed studs is not practical. This had led to the introduction of nailed sheets of shear connectors. The dimensions of the most common stud are 19mm x 125mm and the method of connection to the steel beam is ceramic disk welding. (Aida Rodera Garcia)

2. 4. 1. 1 Headed Studs

The most common form of connecting materials compositely is with the use of headed shear studs. The behaviour of headed studs does not vary significantly when concrete properties are changed. Resistance to shear depends on the number of studs used and performance is less that that achieved by more modern shear connectors such as the Perfobondstrip or a welded T-Section. (Zingoni, 2001)

The advantages of stud connectors is that the welding process is quick and simple, the placement of the studs does not interfere with the placement of reinforcement within the slab and they provide uniform resistance to shear in all directions normal to the axis of the stud. (Johnson, 2004)

2. 4. 1. 2 Oscillating Perfobondstrip

The curved form of an oscillating perfobondstrip provides better force transfer between steel and concrete than a continuous strip. The load capacity of this connector is larger than a headed stud or welded T-Section. This form of connector is most suited to light weight concrete or high strength normal weight concrete. Problems with this form of connection are difficulties in welding the section to the steel beam. (Zingoni, 2001)

2. 4. 1. 3 Continuous Perfobondstrip

The continuous perfobondstrip is similar to the oscillating perfobondstrip but achieves lower resistance values in all categories of concrete type and grade used. For this reason it is not as widely used as the oscillating form although welding is easier.

3. 3. 1. 4 Welded T-Section

Welded T-Section connectors perform very well in comparison to headed studs and achieve the same load resistance as oscillating perfobondstrip. Load capacity increases when Light Weight Concrete or high strength concrete is used.

The strength comparisons of the shear connectors described above are shown in Table 1 below. The results were obtained from Galjaard and Walraven (2001) from tests carried out to Eurocode 4 standards for push-out resistance. It can be seen that large differences in resistance and ductility were observed. (Aida Rodera Garcia)

2. 4. 2 Shear Connector Design

The choice of which shear connector design is open so long as it possesses the ductility and provides the necessary shear and separation resistance to the composite system. Headed studs are the most common form of connection and the design of such will be dealt with in this section.

The design of shear connectors and composite slabs is given in Eurocode 4. Partial safety factors (Î³v) of 1. 25 for ultimate, 1. 0 for serviceability and 1. 0 for fire are specified in the codes. (Steel Construciton Institute, 1994)

2. 4. 2. 1 Spacing

The correct placement of studs along the upper flange of the beam is of great importance. It is important that the flange of the beam be clean, dry and free of contaminants such as paint or fire protection material. A number of conditions for the placement of studs are described below.

The upper flange thickness may not be less than 40% of the diameter of the headed stud.

After pouring, the head of the stud should have a minimum of 20mm cover.

The minimum edge spacing of the headed studs is 20mm, to facilitate welding.

Transverse spacing of headed studs must be greater than or equal to four times the diameter of the headed stud.

Longitudinal spacing of the headed studs must lie between the minimum of five times the diameter of the headed stud and the maximum of 800mm or six times the overall depth of the slab, whichever is smaller.

(ECCS, 1993)

2. 4. 2. 2 Resistance of Shear Connectors

The failure of a composite floor deck slab and the failure of shear connectors occurs due to either the strength of the concrete being surpassed or the strength of the weld connecting the studs to the flange of the beam failing. Shear connection design resistances are taken as the minimum of either the concrete or the headed stud.

The equations for the design resistance of the concrete and the headed stud are given below.

Where:

d is the diameter of the headed stud.

The ultimate tensile strength (fu) is most commonly 450N/mm2 and should not exceed 500N/mm2.

The characteristic cylinder strength of the concrete is given by fck.

Ec is the mean value of the secant modulus of the concrete. The values for different concrete strengths are given in the Annex Table 4.

The value for Î± is governed by the ratio of the height of the slab to the depth. The values of Î± are given below.

For 3 â‰¤ h/d â‰¤ 4, Î± = 0. 2(h/d +1)

For h/d > 4, Î± = 1. 0

The partial safety factor () given by 1. 25 in the ultimate limit state.

(ECCS, 1993)

Figure 10: Bearing stress on the shaft of a Headed Stud Connector (Johnson, 2004)

2. 4. 2. 3 Degree of Shear Connection

The degree of shear connection is based on whether the required numbers of shear connectors necessary for the composite beam to develop its full plastic moment have been installed. If fewer than the required amount necessary have been installed, the moment resistance of the composite system will be less than the maximum.

The degree of shear connection is given by the equations below.

Where Rc denotes the compressive resistance of the concrete slab and Rs denote the tensile resistance of the steel section. Both values are given by the equations below.

Where hc is the depth of the concrete slab above the profiled decking.

Eurocode 4 also provides provision for the minimum for the degree of shear connection based on the span (L) of the composite beam. These ratios are given below.

For:

L â‰¤ 5m, N/Nf â‰¥ 0. 4

5m â‰¤ L â‰¤ 25m, N/Nf â‰¥ 0. 25 + 0. 03L

L > 25m, N/Nf â‰¥ 1. 0

(ECCS, 1993)

Chapter 3

Composite Steel Deck Floors in Fire

3. 1 Background

The performance of composite steel deck floors in fire has been much studied to assess the design considerations that must be implemented and for designing the rules for reinforcement placement. In general, composites perform well in fire due to the insulating properties of concrete and the role of correctly placed mesh reinforcement and metal decking. (BCSA, Corus, SCI, 2007)

Research conducted in the UK has concluded that previous methods of designing composite floor decks for fire scenarios was over conservative and that composite floor performance in many common fire scenarios was satisfactory. (Steel Conctruction Institute, 1991)

Composite steel deck floor systems are typically not provided any fire protection material although the supporting beam to which the floor is connected is fire protected. The profiled decking of a composite floor acts as some of the tensile reinforcement of the system. For this reason, it is important to account for the effects that elevated temperatures will have on the decking. (Steel Conctruction Institute, 1991)

The main contributor to the fire resistance of a composite slab is the embedded rebar mesh in the slab. As the temperature of the profiled decking increases in a fire scenario, the resistance that it provides is neglected. Additional reinforcement in placed in the slab to compensate for the loss of strength of the decking at elevated temperatures. The embedded reinforcement mesh is insulated by concrete and maintains a temperature sufficient for load bearing at the fire limit state. The positioning of rebar within composite floors typically results in higher concrete cover compared to normal reinforced concrete slabs. This results in good fire performance as the temperature of the reinforcement will rarely approach critical levels. The positioning of the reinforcement in the upper of the slab also contributes to controlling spalling in fire.

The decking of a composite does play an important role however in maintaining the integrity of the concrete slab during fire. It limits the passage of flame and hot gases into direct contact with the concrete and controls spalling.

3. 2 Load Resistance in Fire

Design of composite slabs in fire conditions is based on the ultimate limit state properties. A composite floor slab is assumed to behave in bending as either a simply supported or continuous element. The load resistance of a composite floor deck system is due to the floor behaving as a reinforced concrete slab with loads being resisted by the bending action of the slab. Failure of a slab in fire occurs as a result of reinforcement failure. (Corus Construction & Industrial, 2006)

3. 2. 1 Methodology

There are two main methods for calculating the fire resistance efficiency of a composite floor deck system, referred to as the fire engineering method and the simplified method.

3. 2. 1. 1 Fire Engineering Method

The fire engineering method is based on the assumption that in the fire limit state, the plastic moment capacity of the floor is reached at higher temperatures and that redistribution of moments occurs where the slab is continuous. Temperature gradient experiments have produced temperature profiles such as those present in the Eurocodes. These profiles can be used to calculate the capacities of the beam in both hogging and sagging bending. The capabilities of the beams in the fire limit state can then be assessed.

3. 2. 1. 2 Simplified Method

The simplified method involves little or no calculation and relies on test data of actual fires to design the reinforcement in the composite slab. The density of the mesh can be adjusted to account for point loads and increased moment around supports.

In general, the simplified method will deliver a result that demands less reinforcement in the design whilst the fire engineering method will allow greater flexibility in positioning the reinforcement and customising fire resistance time periods.

The use of different grades of concrete will affect the dimensions and composition of a composite slab. Light Weight Concrete (LWC) has better insulating properties versus Normal Weight Concrete and its use will result in thinner slabs.

3. 2. 1. 3 Design Period & Deflection Limits

The fire resistance of a composite floor deck system is measured as the time that a floor system can maintain sufficient load-carrying ability, maintain its integrity or by limiting heat transfer through the slab.

The load-carrying ability of the composite floor system is measured by the amount of deflection that the system undergoes during fire exposure. Deflection greater than the span/30 is deemed critical as is a deflection rate greater than span2/9000d mm/min between deflections equalling span/30 and span/20.

The integrity of the composite floor is deemed satisfactory for fire resistance if it can limit the passage of flame and hot gases.

The insulating properties of concrete are deemed sufficient for fire resistance if after fire exposure, the upper surface temperature of the concrete slab remains below 140°C. (Steel Conctruction Institute, 1991)

3. 2. 1. 4 Reinforcement

Fire resistance of a composite deck is attributed to the positioning of reinforcement in a mesh configuration within the slab. The most common forms of mesh are A142 mesh (6mm wires at 200mm c/c) and A193 mesh (7mm wires at 200mm c/c), the numbers referring to the cross-sectional area of steel per metre run, although larger gauges may be used if necessary. The tensile strength of the reinforcement is typically 450-500N/mm2. The positioning of the mesh is in the upper portion of the slab with a minimum cover and can be arranged to resist hogging or sagging bending or a combination thereof. (Aida Rodera Garcia)

3. 3 The Fire Engineering Method

The fire engineering method for composite slab design is discussed in this section. The partial safety factors at the fire limit state for materials and loads are outlined below.

Materials:

Steel: Î³mr = 1. 0

Concrete: Î³mc = 1. 3

Loads:

Dead: Î³fd = 1. 0

Imposed Î³fi = 1. 0

3. 3. 1 Materials

In conjunction with a suitable design fire scenario, it is possible to account for the reduction in strength of both the reinforcement and the concrete in fire conditions. With elevated temperatures, a reduction factor K may be used to account for the loss of strength associated with the increase in temperature. The table of reduction factors is given in Annex Table 5.

The equations used for assessing the design strengths of the reinforcement and concrete at elevated temperatures including the reduction factor (K) are given below.

Reinforcement:

Concrete

(Steel Conctruction Institute, 1991)

3. 3. 2 Depth

The minimum depth of the concrete slab is taken from the tables below. Different values are obtained depending on the type of decking used, such as trapezoidal or re-entrant, and the concrete grade. This minimum depth satisfies the insulation requirement for composite slabs during fire exposure. Alternatively, the minimum depth may be taken from experimental test results from buildings of a similar design. (Steel Conctruction Institute, 1991) (Aida Rodera Garcia)

3. 4 The Simplified Method

The simplified method consists of installing a layer of mesh (A142, A193 or similar) in the upper layer of the concrete. One of the main differences between the Fire Engineering Method and the Simplified Method is that relatively few calculations are required for the Simplified.

An outline of the Simplified Method is a follows:

Imposed loads on a composite floor deck slab should not exceed 6. 7kN/m2. The mesh size is chosen based on the required fire resistance period and the span of the slab. The minimum cover to any part of the mesh must be at least 15mm and not greater than 45mm.

The span of a composite floor slab designed using the Simplified Method is typically 3. 6m although spans greater than this may be used if adequate calculation is carried out.

3. 5 Comparison of Methods

While no method is definitively better than the other, they both have advantages over the other. The Simplified Method is more economical and is based directly on test results and not on theoretical calculation, which has a tendency to under-estimate the strength of materials. The Simplified Method also takes into account the contribution from the profiled steel deck even though the contribution may be small compared to that from the reinforcement mesh.

The Fire Engineering Method however allows great flexibility in the customisation of the reinforcement and fire resistance periods. It is generally more expensive to design using this method as opposed to the Simplified Method though will result in thinner slabs that utilise more reinforcement.

3. 6 Shear Connectors in Fire

The performance of shear connectors in fire has not been widely studied. One of the major research projects on shear connectors in fire was The Restrained Beam Test conducted by British Steel as part of the Cardington Fire Tests in January 1995.

The test consisted of the heating of a secondary beam and an area of the surrounding slab on the seventh-floor of the test structure. The steel section tested was a 305×165 UB40 that was heated along 8m of its 9m length. Only the top 70mm of the concrete slab was taken into account. This was the maximum height of the slab above the troughs of the profiled decking. (Huang, Burgess, & Plank, 1999)

The temperature distributions in the steel beam and concrete slab were taken as averages of the test results recorded across the cross-sections of the components. The temperature of headed studs exposed to fire was approximated as 75% of the temperature reached by the top flange of the steel section. (Huang, Burgess, & Plank, 1999)

The degree of shear connection in the heated beam was assumed to be partial whilst the rest of the composite floor deck systems in the surrounding area were modelled as having full shear interaction.

Analysis of the test results showed that the deflection at the mid-span of the heated beam increased with temperature. It was concluded from this that the assumption that partial interaction was corre