INVESTIGATIONS ON FLEXURAL CAPACITY OF STEEL CONCRETE COMPOSITE DECK WITH DIVERSE BOND PATTERNS

A Synopsis submitted to Gujarat Technological University

in

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by

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Content

Synopsis

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1. Abstract

Profile steel sheet concrete composite slab are gaining usage in modern construction practice in many parts of the world, but in India still it is in a nascent stage. Considerable reduction in the structural weight and reduction in construction time, are key advantages of composite deck system compared to the ordinary reinforced concrete slabs.

The composite deck design is not much explored in India and there are no guidelines available to design composite deck as per Indian code. There is no quality control over the dimensions of mechanical interlock at most of the local manufacturing units. Products which exhibit weak mechanical interlock is uneconomic and current market products raise questions about the reliability of steel decking to act as reinforcement.

The production cost of deck increases by about 25 % using embossment as a mechanical interlock. For developing any new pattern of mechanical interlock, large scale testing is required. Various experimental methods are developed to estimate the capacity of composite deck. Most of the research work is focused on large scale testing. Few study shows the research on small scale test but in those cases, the test procedure does not represent the actual loading conditions of the slab.

The purpose of this research is to develop understanding about the behaviour of steel concrete composite deck. The work comprises of studies on flexural capacity of steel concrete composite deck as per various International codes. It investigates the effect of bond between the metal deck and concrete to enable better composite action by experiments. The another aim is to reduce the dependency on full-scale bending test and to represent the actual behavior of slab through relatively small scale test.

The research includes theoretical analysis and comparative studies on steel concrete composite deck. It entails development of design chart for different material grades, different

profiled sheet thickness and slab thickness for a particular geometry considering full bond. It includes experimental work for bending tests of composite slabs with different bond patterns. The various analytical methods are studied and compared to determine the effect of the bond.

The results of the investigation depict, the generalized program developed to calculate flexural capacity under full bond, which can be used for any geometry, any steel grade and any concrete grade, whereas the software available by the particular manufacturer can analyse only a specific deck geometry. It involves, derivation of limiting value of neutral axis, considering stress block as per Indian standard. The result of parametric study represents an increase in grade of steel, significantly increases flexural capacity. The experimental investigation shows that different mechanical interlocking systems exhibit different composite action and different failure modes. The bond protrusion has a significant effect on slab strength.Results of small-scale test with ductile failure show good agreement with large scale tests. Small scale one wavelength test is a feasible option for evaluating composite action of deck, which can be simply implemented by Indian small scale industry, developing new mechanical interlock pattern and/or the local user without much cost escalation.

2. Brief Description on the State of Art of Research Topic

Over the past four decades, many researchers have performed full scale and small scale tests on the composite slabs. In early 1976, Porter et al. carried out full-scale tests on composite slabs to establish shear-bond failure mechanism. They have reported several parameters which govern the composite behavior and recommended the design equations for the shear-bond capacity which is derived from the series of performance tests on the slabs. To substantiate the effects of adhesion bonding, mechanical interlocking and surface friction, tests have been performed and semi-empirical formulations have been developed by Schuster-Ling,1980 and Luttrell- Prassanan,1984. Patrick and Bode,1990 have developed a partial shear connection method based on partial interaction theory. Patrick and Bridge,1994 have stated that loading pattern for a particular case of profile sheet will have a significant influence on the outcome of tests result. Michel Crisinel, 2004 raised the concern about costly and time-consuming large-scale laboratory tests. They have proposed a new approach which combines results from standard material tests and pull out tests with a simple calculation model to obtain the moment–curvature relationship. J. Roger,2006 has stated that the safe load tables provided by the manufacturer for the particular type of configuration may not be strictly in accordance with Eurocode methods.

Use of sheeting outside the country of origin may require verification. As an alternative to full-scale testing, Redzuan Abdullah and W. Samuel Easterling, 2007 have presented new elemental test method. In order to investigate the shear-bond strength of square shape embossment pattern, Marimuthu et al., 2007carried out experimental work on eighteen slabs. Shiming Chen et al., 2011 have proposed an improved method by performing a detailed experimental study on shear bond failure. K. N. Lakshmikandhan et al., 2013 have experimentally studied three types of mechanical connector and found that three connector schemes exhibited full shear interaction and produced a negligible slip.

Literature study reveals that most of the research work focus on the development of composite deck sections and its behavior considering the full-scale test. Very few study shows the research on small scale test. Moreover, a product developed by the manufacturer may not be strictly in accordance with standards and its use outside the country of origin require further confirmation.

3. Objectives and Scope of work

The research work focuses on, analytical studies on composite deck system and composite action with different bond patterns between steel and concrete in the composite floor system, to appreciate and compare the effect of different interface topology.

The objective of the work is to analyze the flexural strength of composite deck analytically and experimentally with different bond patterns.

The study involves theoretical analysis, comparative studies and development of design chart for different material grades, profiled sheet thickness and slab thickness for a particular geometry considering full bond. It also consists of a laboratory test program which includes the three and one wavelength test on composite decks considering series of line loads with different bond patterns.

4. Original contribution by the thesis

Most of the earlier investigations indicate the development of composite deck sections in different parts of the world. The composite deck design is not much explored in the Indian context. Also, for geometrical parameters and design of composite slab with profile deck no guidelines are available in Bureau of Indian Standards (BIS).Moreover, most of the research work focuses on the behavior of composite deck considering a full-scale test of the deck.

However, no specific work has been done so far for the composite slab with variation in bond pattern with small scale bending test. Before a design procedure can be formulated, it is essential to obtain a better understanding of the behaviour of composite slab. Hence, a theoretical analysis as per various standards and experimental programme to study the flexural capacity of the composite slab with varying bond patterns is a research gap and it is hoped that this investigation will make a contribution.

5. Research Methodology

For achieving objectives of the research, parametric study, experimental work, and analytical study is done. Research methodology consists of analytical study of the composite deck with full interaction using Euro, British, American standards and Indian standard stress block. Parametric study of composite deck design with variations in geometrical parameters. Design of geometry and properties for experiments, based on the Euro standard. Experimentation with variation in bond patterns considering different wavelengths. An analytical formulation for the flexural capacity of composite deck.

6. Data Analysis and Interpretation

6.1 Theoretical study

Comparison for flexural capacity is made between Euro standard EN 1994-1-1:2004, British standard BS-5950: Part-IV,1994, Steel Deck Institute-ANSI-2011 and Indian standard stress block. Euro and British standard assume rectangular stress block and for Indian standards partly parabolic and partly rectangular stress block is used. American national standard institute follows the cracked section moment of inertia and simple bending theory to calculate the flexural capacity. All countries have different factors of safety for profile deck. The comparison is done with international standards and thickness variation for profile configuration as shown in Fig.1.The results of flexural capacity using four different standards versus thickness of a profile are summarized as per Fig.2.

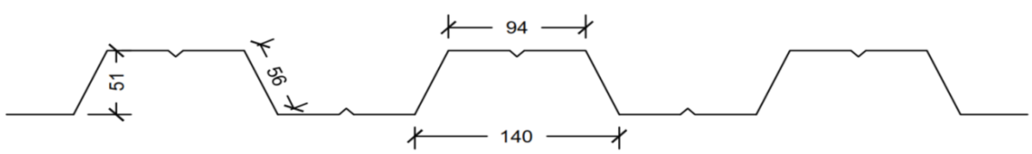


Fig.1. Geometry of Profile sheet

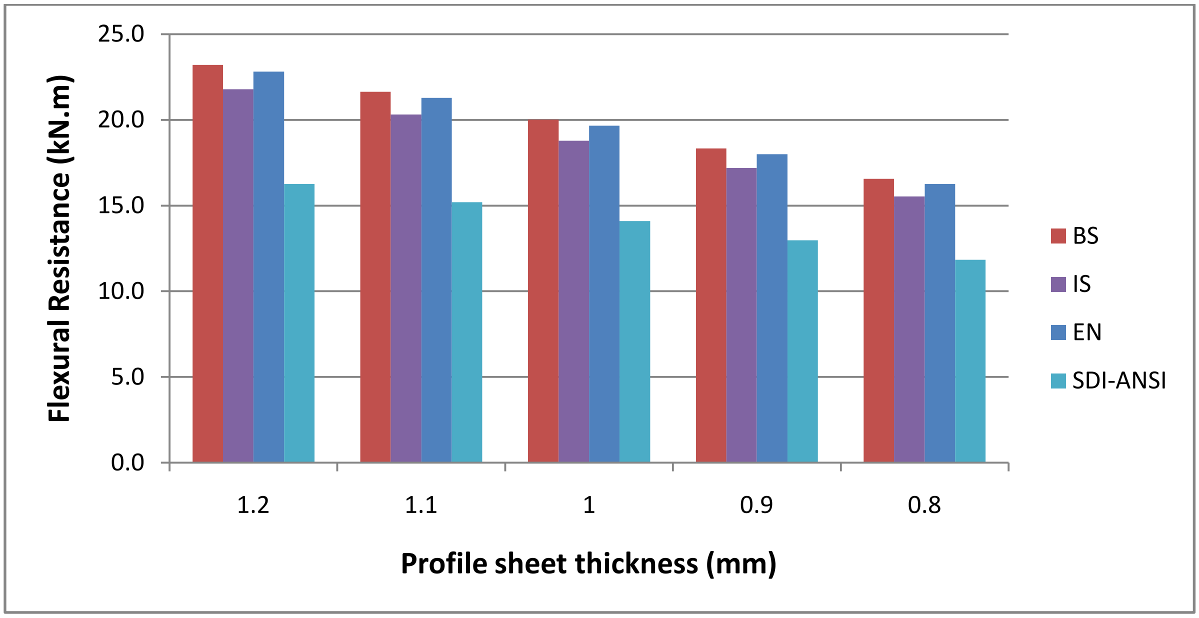


Fig.2 Flexural Resistance Vs Sheet thickness considering different standards

6.2 Parametric Study

For selection of geometry and further analysis Euro Standards EN 1994-1-1:2004 are considered. As profile sheets are available in various size, steel grade, thickness and shape, a parametric study is carried out for analyzing the flexural capacity of particular pattern of composite deck. A program is developed as per Euro standard to study the important geometrical parameters, which influence the flexural capacity. The numerical problem configuration is solved with program and software 'Comdek' for flexural capacity. In the case of flexural failure, it is also necessary to ensure the ductile behaviour of steel concrete composite deck analytically. Hence, the value of the balanced depth of neutral axis is developed for different steel grade to check the actual depth of neutral axis under full composite action. Neutral axis depth is calculated for commonly used steel grade of profile deck considering strain diagram of singly reinforced R.C.C. section.The trapezoidal shape of profile as per Fig 1 is considered for calculating flexural capacity and depth of neutral axis. Parameters are varied like depth of deck (90 mm to 120 mm) (Fig.3), grade of concrete (25 N/mm^2 to 40 N/mm^2) (Fig.4) and grade of steel (230 N/mm^2 to 450 N/mm^2) (Fig.5).

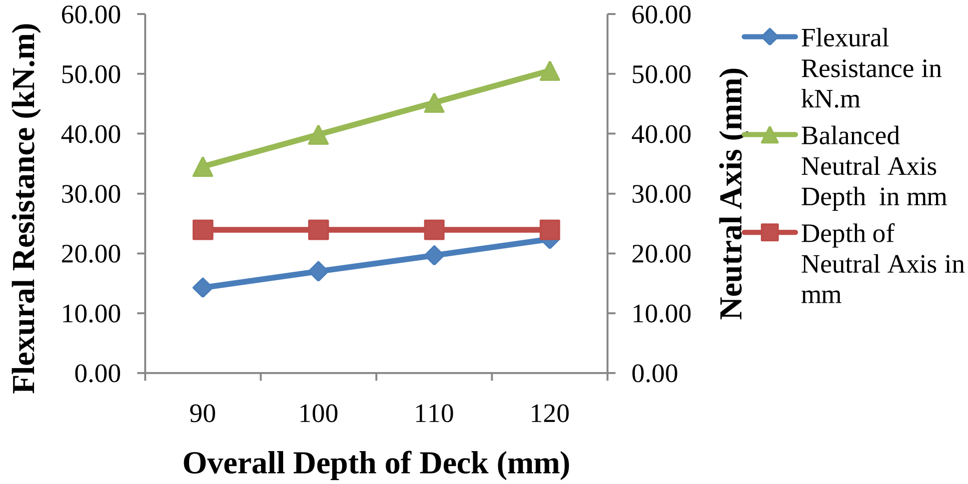


Fig.3 Variation in overall depth of deck from 90 mm to 120 mm

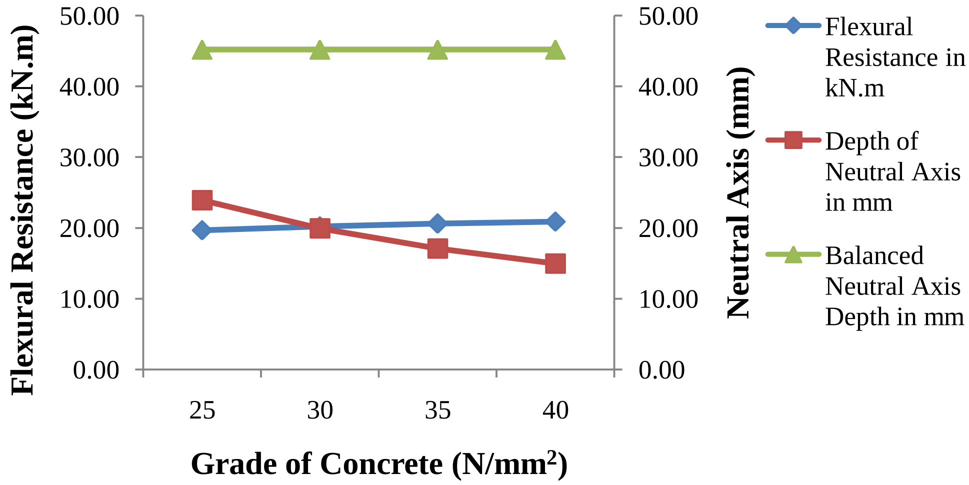


Fig.4 Variation in concrete grade from 25 N/mm^2 to 40 N/mm^2

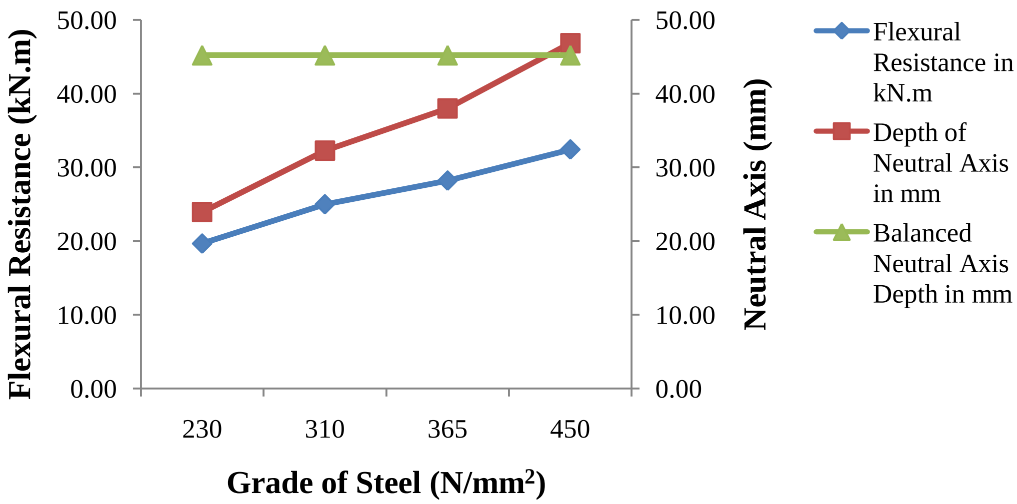


Fig.5 Variaton in steel grade 230 N/mm^2 to 450 N/mm^2

6.3 Results: Theoretical Study and Parametric Study

1. Flexural capacity of deck is calculated considering full bond with various design standards. It is found that British standard gives the highest value of flexural resistance over other standards.
2. The generalised program is developed to calculate flexural capacity and parametric study of composite deck. The results of the program are compared with software 'Comdek' for the composite slab. However, software has limitations that only steel profiled sheet manufactured by Tata steel and steel grade of 280 N/mm^2 and 350 N/mm^2 is analysed by 'Comdek' software. A concrete grade below C25 cannot be analysed.
3. A parametric study shows that flexural capacity changes with a change in grade of concrete, grade of steel and overall depth of deck. For the deck analyzed, 57.10% increase in flexural resistance is found on increasing overall depth from 90 mm to 120 mm. If a grade of concrete is increased from 25 N/mm^2 to 40 N/mm^2, an increase in moment of resistance is found by 6.18 %. For a higher grade of steel varying from 230 N/mm^2 to 450 N/mm^2, 64.78% increase in the moment is obtained. The increase in grade of steel significantly increases the value of flexural resistance.
4. Limiting value of neutral axis for a balanced section of a composite deck is developed, which should be analysed for any composite deck design to ensure under reinforced section theoretically.

6.4 Experimentation

Geometrical parameters as per Euro standard are considered for fabrication. Composite specimens with 1.5 m span are tested under uniformly line loads in such a way that one-way bending takes place. Experimental set up is as shown in Fig.6 First set of experiments are carried out with eight specimens of three wavelengths (Fig.7 (a)) out of which one set was embossed and three sets were unembossed. Different bond patterns such as welded hemisphere on the surface of the deck, chemical agent and cross stiffening plates are provided for composite action to arrive at the best possible system. For the second set of experiments, twelve specimens of one wavelength (Fig.7(b)) are tested under line loads. Out of twelve specimens, four specimens are embossed and other eight are unembossed with different bond patterns. Profile decks were tested for six diverse bond patterns such as bolt connection with a different orientation, circular arc bend in webs, straight stiffeners and pressed embossments. Concrete mix of M25 grade is designed as per Indian standards. After 28 days, concrete compressive strength is determined from testing.

In all cases, three deflectometers are placed beneath the bottom edge of the deck, one at mid-span and two at a quarter span of the deck. Two dial gauges are fixed on steel face and concrete to measure relative slip. For each specimen set, the load at first crack, load at significant end slip, maximum load and corresponding deflections are measured. Load Deflection curves and load slip curves are established for each set of experiments (Fig.8 to Fig.13). For all the specimens, failure mechanism, composite action and separation between the steel deck and concrete are observed. Experimental flexural capacity is calculated at the load at initiation of slip and loss of composite action. Significant observations are listed in Table-1.

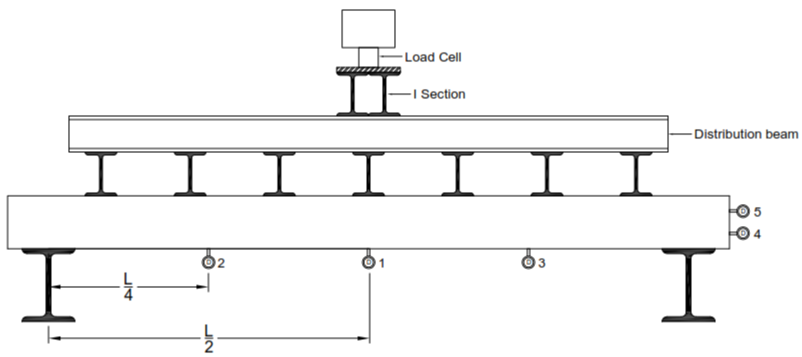


Fig.6 Experimental setup

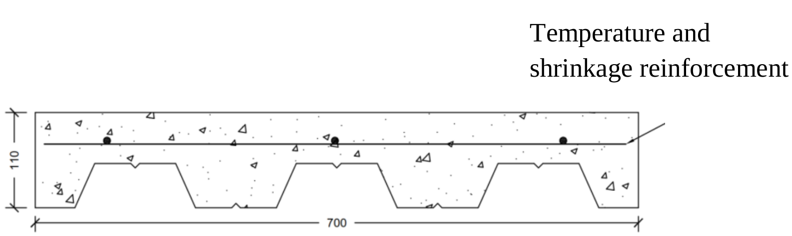


Fig.7 (a) Three wavelength specimen

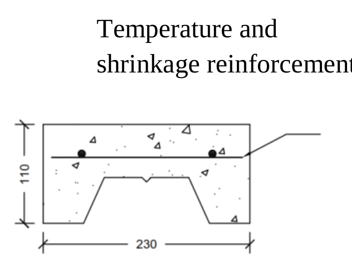
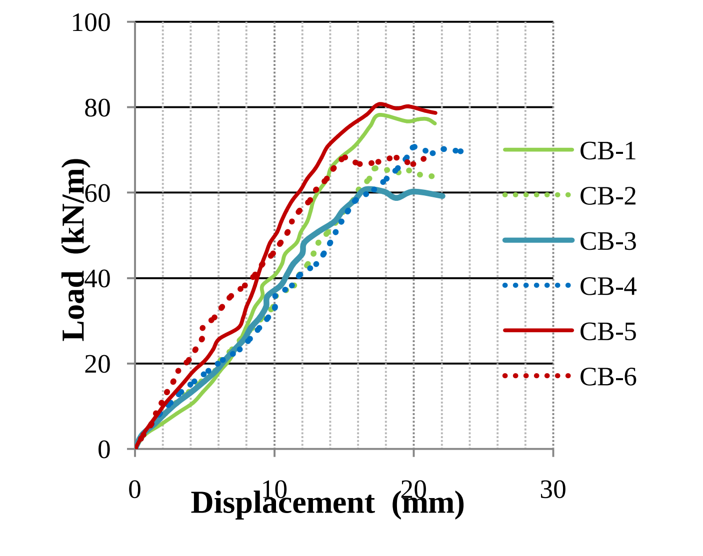


Fig.7 (b) One wavelength specimen



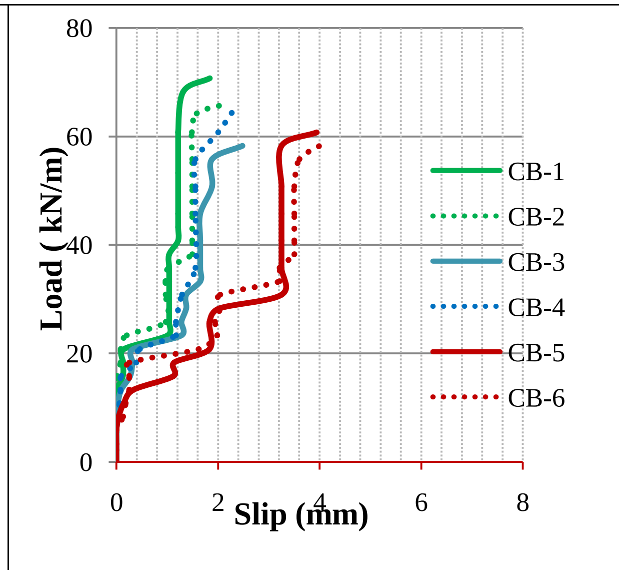
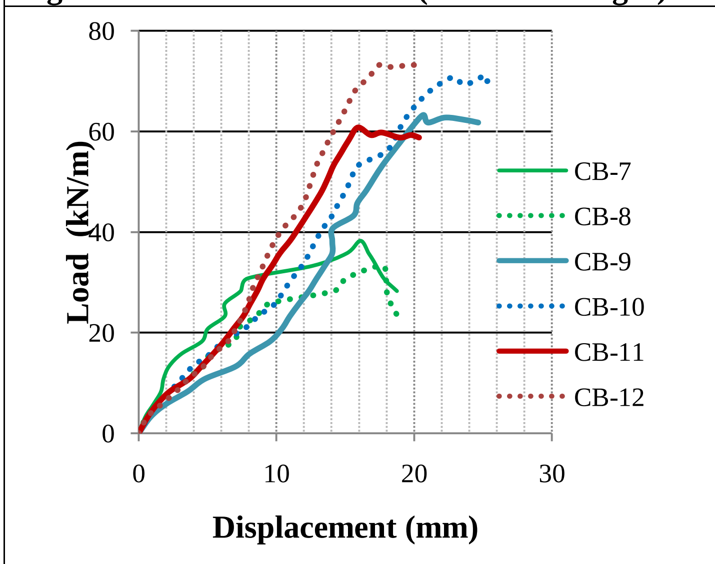


Fig.8 Load Deflection curves (One Wavelength)

Fig.9 Load slip curves (One wavelength)



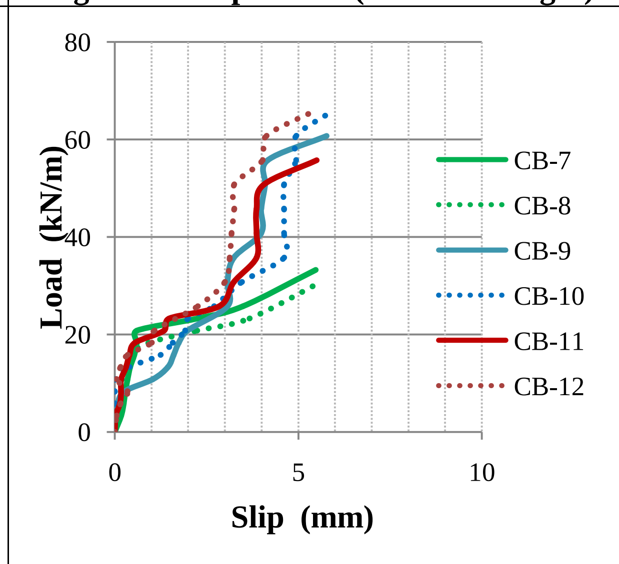
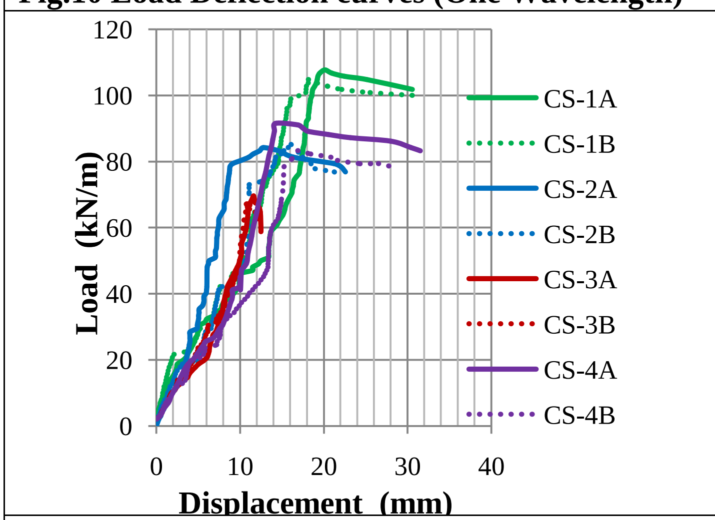


Fig.10 Load Deflection curves (One Wavelength)

Fig.11 Load slip curves (One wavelength)



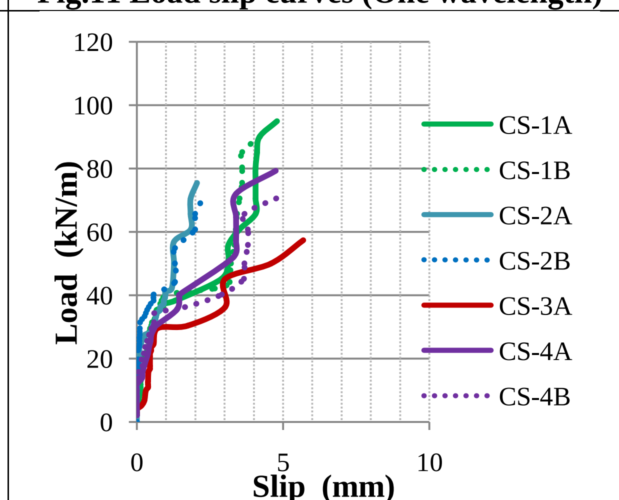


Fig.12 Load Deflection curves(Three Wavelength)

Fig.13 Load slip curves(Three Wavelength)

6.5 Results and Discussions: Experimentation

The full composite action is found in the loading range prior to the onset of cracking in most of the specimens. Once the cracking initiates, mechanical interlock has started resisting the interface force. Subsequently, the separation between the steel deck and concrete is observed in the specimens. Small cracks due to bending were also observed in the centre of moment region in most cases. In the first phase of experiments on three wavelengths, it is found that, among all the four bond patterns, a chemical bond (CS-3) has shown brittle behavior with least load carrying capacity, maximum slip and sudden loss of composite action. Hemisphere type bond pattern (CS-2) develop good composite action with minor slip and no vertical separation. Embossed deck (CS-1) and cross stiffener deck (CS-4) has shown less composite action than that of the hemisphere. Experimental results reveal the satisfactory composite action of unembossed deck with the hemisphere.

In the second phase of one wavelength specimen, topology with bolts (CB-1-2, CB-3-4) and arc- bolt (CB-5-6) combination behaved in a similar way. The use of bolt creates an additional anchorage for the composite deck which develops tensile force in sheeting by, mechanical bond and slip resistance. The steel panel, confined by concrete around the protrusion show significant increases in slip resistance.

The composite specimens with lateral stiffening plate (CB-7-8) failed in a sudden manner, showing potential crack at the location of the stiffener. The failures of the specimens with pressed in-in (CB-9-10)and in - out embossment (CB-11-12) are found with major slip and vertical separation. In spite of having a high yield strength of sheets and higher cost as compared to other systems, much higher load carrying capacity was not observed in pressed embossment decks.

The strength of composite specimens at failure was very high in most of the cases, owing to the ductility of the system and reserved strength. It is also due to the addition of reinforcement for temperature and shrinkage which is provided below the calculated neutral axis of the specimen. Experimental investigation and comparison are focused on composite action and failure pattern. Experimental flexural capacities are considered at load at initiation of slip
(1 mm slip) and load at a significant loss of composite action(3 mm slip). Experimental values are tabulated as per Table-1. Comparison between three wavelengths and one wavelength patterns shows, one wavelength specimens behaved in the same manner and gives satisfactory results.

Table -1 Experimental Observations

Specimen	Topology at interface	Mei (slip-i)	M es (slip-s)	Observation of slip	Observation of vertical separation	Failure
		(kN.m)	(kN.m)			
CB1-2	Bolt Head	4.64	7.47	Negligible	Negligible	Ductile
CB3-4	Bolt Shank	4.40	6.53	Negligible	Negligible	Ductile
CB5-6	Arc Bend and Bolts	3.46	6.05	Minor	Minor	Ductile
CB7-8	Straight Stiffeners	4.17	4.64	Major	Major	Brittle
CB9-10	Pressed in – in embossments	2.51	5.35	Major	Major	Ductile
CB11-12	Pressed in – out embossments	3.66	5.82	Major	Major	Ductile
CS1A-B	Oval shape embossment	7.83	9.38	Minor	Major	Ductile
CS2 A-B	Welded Hemisphere	8.51	11.98	Minor	Negligible	Ductile
CS3 A-B	Chemical Bond	6.00	7.16	Major	Major	Brittle
CS4 A-B	Cross Stiffener	7.06	9.57	Minor	Minor	Ductile

6.6 Analytical Approach: Composite action

As there is variation in parameters of the composite deck such as concrete strength, steel strength and sheet thickness, flexural capacitates of different specimens are calculated analytically considering all material and geometric variations. The analytical flexural capacity of the decks was predicted using four different approaches (i) Luttrell's Lug factor approach (ii) Euro standard (iii) First Yield Approach(iv) Composite Beam approach.

In Luttrell's approach, empirical formulae, developed by Lutrell for type I Lug is considered. The approach considers the geometrical parameters related to bond and deck depth. Calculations by Euro standards considering the full interaction between concrete and steel is made as per discussion in section 6.1. First yield method, tensile forces T_1, T_2, T_3 at the top flange, web and bottom flange of the deck, respectively, are considered. Composite Beam Analogy method is applied considering the effect of actual connectors and connectors for full interaction in relevant cases.

1. Luttrell Lug approach

The method developed by Luttrell and Prassanan [4] (1986) is based on determination of flexural capacity of the deck by applying three "relaxation factors", which influences shape, deck dimension and bond/protrusion configuration. The generalized formula for flexural capacity is calculated, considering any height of mechanical interlock.

$$M_T = K\,M_F\ ,\ M_F = A_s\,F_y\,e\ \text{ and }\ K = \frac{K_3}{K_1 + K_2}$$

$$k1 = \frac{1}{\sqrt{D_d}} + \frac{t}{P_h\,D_d}\quad ,\ k2 = \frac{100\,(t)^{1.5}}{D\,\sqrt{P_h}}\ ,\ k3 = 0.87 + 10^{-3}\left(\frac{B}{Bc}\right)(69 - 2.2)\left(\frac{B}{Bc}\right)$$

2. First Yield Method

The flexural capacity of the slabs is predicted, using the moment at first yield. First yield method is developed by Heagler (1992) for the flexural capacity of composite deck. It is based on a transformed area and by dividing the tensile force of the deck to each of the flanges (T_1, T_3) and the web (T_2) separately as per Fig.14. The method predicts the performance of a deck considering steel at different levels. The effectiveness of protrusion is not considered in this method.

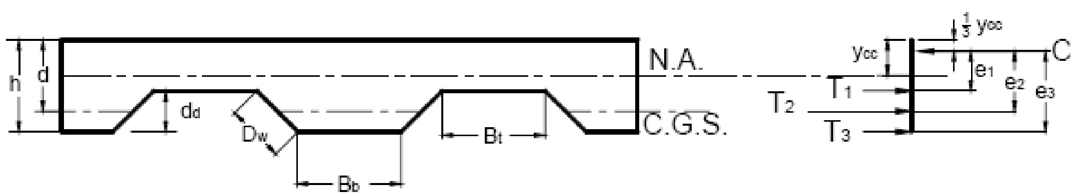


Fig.14 First Yield Theory

$$M_T = (T_1\,e_1 + T_2\,e_2 + T_3\,e_3)$$

3. Composite beam analogy

Composite slabs are made from similar components as a composite beam, namely a steel section (profiled sheet) and a concrete slab which are connected to resist longitudinal slip. It is therefore assumed that a composite slab with bolts as connectors, will behave as a composite beam. In the calculation, the connectors for full interaction and connectors provided, are put as input values. The flexural capacity of the composite deck is found out by

$$M_T = M_P + \frac{N_P}{N}(M_F - M_P)$$

6.7 Results: Analytical Approach

Different methods of analysis for flexural capacity have been studied. Lutrell lug approach and Composite beam analogy approach consider the effect of composite action in flexural capacity. Another method such as Euro standard and first yield method analyses flexural resistance considering full composite action. The aforesaid methods are used as one of the input parameters for Lutrell lug approach and Composite beam analogy approach. Composite beam analogy approach is used only in the cases with bolt as connectors. Lutrell lug approach can be considered, when dimensions of protrusion are known, so it is used in appropriate cases only in this work. First yield method gives conservative result considering full bond. Representation of analytical results is as per Table 2.

Table -2 Analytical flexural capacities with different theories

Specimen	Mt1 (kN.m) Lutrell's approach	Mt2 (kN.m) Euro stress block approach	Mt3 (kN.m) First yield approach
CB1-2	5.07	5.335	3.653
CB3-4	5.13	5.331	3.653
CB5-6	--	5.343	3.653
CB7-8	--	5.292	3.653
CB9-10	4.61	7.927	5.797
CB11-12	4.62	7.939	5.797
CS1A-B	11.80	14.220	9.913
CS2 A-B	9.34	14.220	9.913
CS3 A-B	--	14.220	9.913
CS4 A-B	--	14.220	9.913

6.8 Experimental and Analytical Comparison

The comparison between experimental flexural capacity at slip initiation, potential slip and theoretical capacity with Euro standards are presented in Fig.15 and Fig.16. It shows that specimen with bolt patterns almost attains almost full flexural capacity. These specimen also resist significant slip after slip initiation.

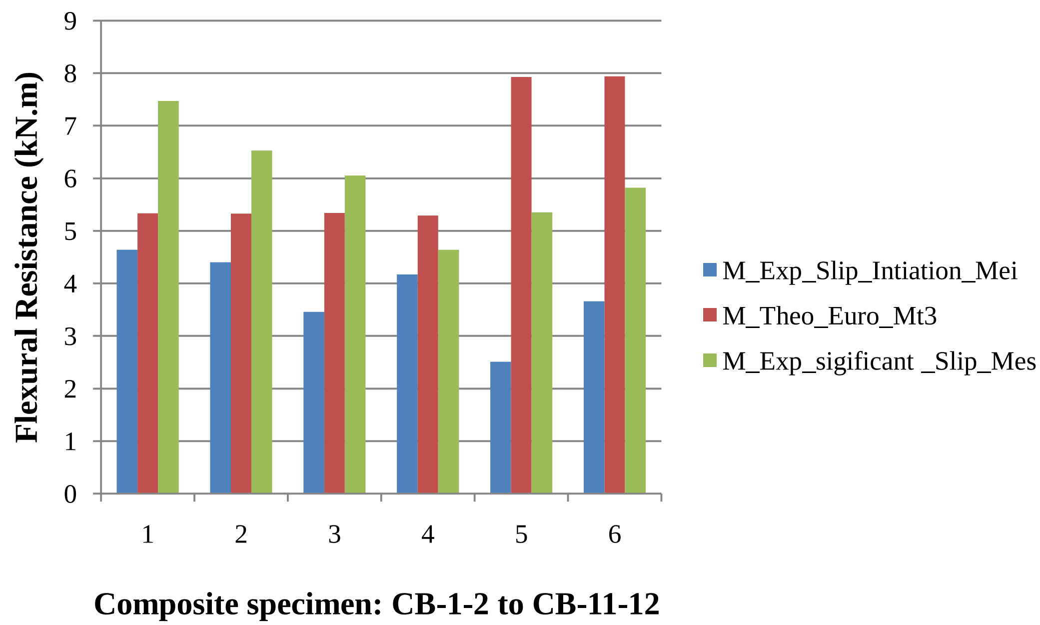


Fig.15 Flexural Resistance -Specimen CB

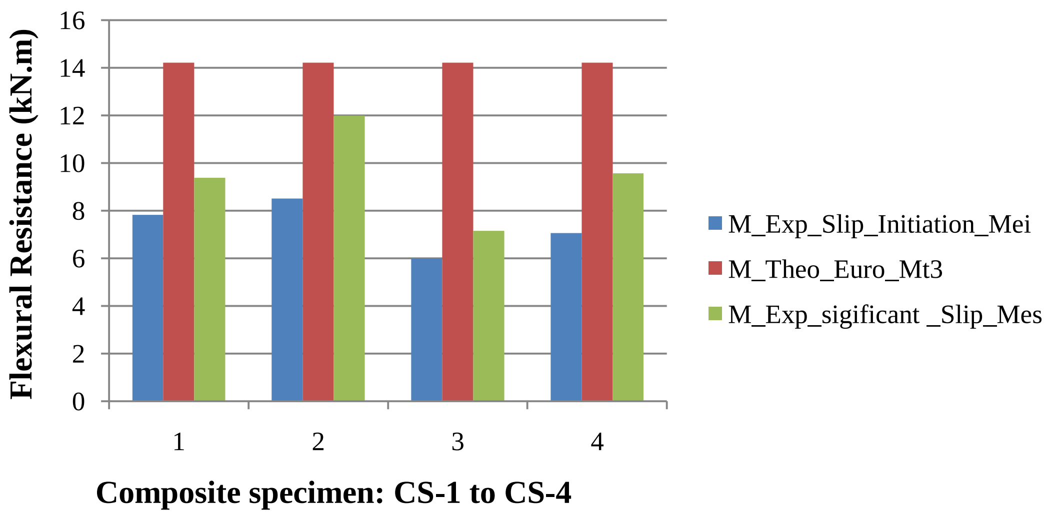


Fig.16 Flexural Resistance -Specimen CS

7. Achievements with respect to Objectives

In the research conducted, following work is done with respect to objectives.

1. Theoretical analysis for flexural capacity considering full bond as per various standards is made so as to compare with Indian conditions, as there are no guidelines about the composite deck in Indian standard.

2. Comparative studies are made and design charts are developed for different material grades, profiled sheet thickness and slab thickness for a particular geometry.
3. Experiments on three and one wavelength composite decks considering with different bond patterns are performed. A suitable configuration of bond pattern is recommended for better composite action. Analytical formula considering the composite actions are studied and compared.

8. Summary

The research works emphasis on the theoretical as well as experimental behaviour of the composite deck and effectiveness of bond. The results of the analytical investigation depict the generalized program developed to calculate flexural capacity under full bond, which can be used for any geometry, any steel grade and any concrete grade, whereas the software available by the particular manufacturer can analyse only a specific deck geometry. It involves derivation of limiting value of neutral axis. The result of parametric study represents an increase in grade of steel, significantly increases flexural capacity.

The experimental investigation shows that different mechanical interlocking systems exhibit different composite action and different failure modes. It gives an idea to the user that if the profile sheet used in construction is without embossment or improper embossment quality (Chemical bond case and straight stiffener case) it will lead to brittle failure. In cases of all diverse bond patterns, specimens with a chemical bond, straight stiffeners and pressed embossment showed major slip and vertical separation. So the aforesaid bond patterns are not suggested for further development. Specimen with oval embossment as well as pressed embossment did not show significantly good composite actions over bolt topology. Specimen with bolts have significantly improved composite interaction over all other bond patterns.The bond protrusion has a significant effect on slab strength.Results of small-scale test with ductile failure show good agreement with large scale tests. Small scale one wavelength test is a feasible option for evaluating the composite action of deck, which can be simply implemented by Indian small scale industry or developing new mechanical interlock pattern by the local user without much cost escalation. Analytical approaches considering composite action is simple and provides good prediction of flexural capacity in recommended cases.

9. Conclusions

Detailed investigations on steel concrete composite deck are made analytically and experimentally. To achieve the better composite action between steel and concrete, different bond patterns are explored. The effect of composite action is studied analytically by two different theories. The resulting conclusions are listed as follows:

1. The generalized program developed to carry out an analytical and parametric study of composite deck can be used for any variation in geometrical parameters or material parameters. By that, ability of cold-formed section to mould into optimum shape of profile sheet can be greatly appreciated.
2. The increase in flexural resistance of about 4 % and 6% is found in Euro standard and British standard respectively as compared to IS stress block. SDI-ANSI gives conservative results of flexural capacity.
3. The increase in grade of steel significantly increases the value of flexural resistance by 64.78% for a investigated profile.
4. For three wavelength specimens, oval embossment profiles have reduction in composite action by 8% as compared with hemisphere profiles and 57% when compared with bolt patterns.
5. For achieving full composite action, bolt pattern is found effective than embossment. In case of all diverse bond patterns, specimen with bolts have significantly improved composite interaction over all other bond patterns with ratio of experimental to analytical composite flexural capacity of 0.91 at slip initiation.
6. One wavelength test predicts reasonably accurate flexural capacity of deck. It reduces the experimentation cost without compromising with the bending behaviour of the slab. It is recommended for future research and development of any profile sheet.

10. Awards and Publications

1. **Awarded by Government of Gujarat-Science and Technology Research grant, Principal Investigator, 2015, GUJCOST, Department of Science and Technology**

2. Comparative study of moment carrying capacity of composite deck, *Journal of information, knowledge and research in civil Engineering*,2012, ISSN: 0975 – 6744, Volume 2, Issue 1, pp 60-62

3. Structural cold formed steel, steel-concrete composite and structural stainless steel: A critical review of research and opportunities, *Structural Engineering Convention,* 2012, SEC-12, S.V.N.I.T., pp 729-735

4. Parametric Study of Open Trough Steel Concrete Composite Deck, *Nirma Journal of Engineering and Technology,* 2014, ISSN: 2231-2870, pp 12-14

5. Load carrying capacity of composite deck with different bond patterns, *EUROSTEEL 2014, 7th European Conference on Steel and Composite Structures, Italy,* 2014, pp 591-592

6. Investigations on composite deck with different interface connections, *Journal of Structural Engineering-JOSE*,2016, Vol. 42, no. 5, pp 386-392 **(SCI Indexed)**

11. References

1. Slutter, R. G. and Driscoll, G. C. Jr.,1963 "Flexural strength of steel and concrete composite beams", *Fritz Laboratory Reports*, Paper 1806

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Annexure-I

Publications