

**NONLINEAR FINITE ELEMENT ANALYSIS OF STEEL-CONCRETE
COMPOSITE SLABS USING EXPLICIT DYNAMICS PROCEDURE**

MOHAMMAD JOSHANI

A project report submitted in partial fulfillment of the
requirements for the award of the degree of
Master of Engineering (Civil-Structure)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

APRIL 2010

ABSTRACT

Composite slab construction using permanent cold-formed steel decking has become one of the most economical and industrialized forms of flooring systems in modern building structures. Structural performance of the composite slab is affected directly by the horizontal shear bond phenomenon at steel-concrete interface layer. This study utilizes 3D nonlinear finite element quasi-static analysis technique through explicit dynamics procedure to analyze the shear bond damage and fracture mechanics of the composite slabs. Cracking of the plain concrete over the corrugated steel deck has been modeled considering the mixed modes fracture mechanisms by means of concrete damaged plasticity model available in ABAQUS software version 6.9. The interface layer damage was simulated with cohesive elements presented in ABAQUS software considering three modes of fracture. Cohesive fractures properties such as fracture energy and initiation stress have been derived from horizontal shear stress versus end slip curves which were extracted from bending test of a series of small scale specimens. The proposed model is verified through comparison with experimental data which demonstrated that the results of the numerical analyses match with valid experimental results. Therefore these calibrated and validated models can predict the structural response of steel-concrete composite slabs. This will reduce the cost of empirical works which in accordance with present design specifications are mandatory in order to investigate the behavior and load bearing capacity of such structural systems.

ABSTRAK

Pembinaan papak rencam dengan menggunakan deck keluli terbentuk sejuk yang kekal merupakan salah satu jenis sistem papak yang paling ekonomi bagi struktur bangunan moden. Prestasi struktur bagi papak rencam dipengaruhi secara langsung oleh fenomena ikatan ricih mengufuk di antara muka keluli dan konkrit. Dalam kajian ini, analisis 'quasi-static' unsur terhingga 3D yang menggunakan prosedur 'explicit dynamics' telah dijalankan bagi menilai kerosakan ikatan ricih mengufuk dan mekanik retakan pada papak rencam. Retakan pada konkrit di atas dek keluli beralun telah dimodelkan dengan mengambil kira mekanik retakan dengan mod tergabung. Model kemusnahan plastic yang terdapat dalam perisian ABAQUS telah diguna dengan mengambil kira tiga mode retakan. Kemusnahan pada antara muka keluli dan konkrit telah dimodel dengan unsur 'cohesive'. Sifat retakan 'cohesive' seperti tenaga retakan dan tegasan pemula telah diterbitkan daripada graf tegasan ricih mengufuk lawan gelangsaran hujung yang diambil daripada ujian lenturan bersaiz kecil. Model analisis yang dicadangkan dalam kajian ini disahkan kejituan dengan membuat perbandingan antara hasil analisis dengan data ujikaji. Hasilnya, model analisis ini boleh diguna untuk menilai gerak balas struktur papak rencam. Hal ini boleh mengurangkan kerja ujikaji yang dahulunya mesti dilakukan untuk menentukan kelakuan sebenar dan kebolehtanggungan beban system papak rencam.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	x
	LIST OF FIGURES	xi
	LIST OF APPENDICES	xx
	NOMENCLATURES	xxi
I	INTRODUCTION	1
	1.1 Introduction to Steel-Concrete Composite Slabs	1
	1.2 Problem Statement	8
	1.3 Aim of Study	10
	1.4 Objectives of Study	10
	1.5 Scopes of Study	11
	1.6 Organization and Outline of Thesis	12
II	LITERATURE REVIEW	13
	2.1 Introduction	13
	2.2 Fracture Mechanics and NFEA	14

2.2.1	Fracture Modes	16
2.2.2	Composite Slab Behavior with Respect to Fracture Mechanics	17
2.3	Simulation of Composite Slabs	19
2.4	Explicit Dynamics Procedure	21
2.5	Introduction to Cohesive Fracture Theory	22
2.5.1	Concept of Cohesive Zone Model	24
2.5.2	Inter-layer Damage Modeling using Cohesive Element	26
2.5.3	Cohesive Elements and Insertion Algorithms	26
2.5.4	Cohesive Element Formulation	28
2.5.5	Traction Separation Law, TSL	30
2.5.6	Interfacial Material Properties	31
2.5.7	Interface Debonding Initiation and Propagation	32
2.5.7.1	Constitutive Equations for Interface Damage	32
2.5.7.2	Mixed-mode Debonding Criterion	34
2.5.7.3	Damage Evolution Law Implementation	36
2.6	Damaged Plasticity Model for Concrete	42
2.6.1	Post-failure Stress-Strain Relation	46
2.6.2	Fracture Energy Cracking Criterion	47
2.6.3	Defining Compressive Behavior	48
III	METHODOLOGY	50
3.1	Introduction	50
3.2	Development of the FE model	51

3.2.1	Models geometry and characterization	51
3.2.2	Finite Element Mesh Generation	57
3.2.3	Concrete Properties Definition	60
3.2.4	Steel Properties Definition	64
3.2.5	Interface Layer Properties Definition	65
3.2.6	Boundary Conditions	68
IV	RESULTS AND DISCUSSION	70
4.1	Introduction	70
4.2	Case A (3VL16-4-7.5 composite Slab)	73
4.3	Case B (3VL16-8-7.5 composite Slab)	91
4.4	Case C (3VL16-10-7.5 composite Slab)	107
4.5	Case D (3VL16-12-5 composite Slab)	117
4.6	Case E (3VL16-14-5 composite Slab)	128
V	CONCLUSIONS & RECOMMENDATIONS	141
5.1	Conclusions	141
5.2	Recommendations	144
	REFERENCES	145
	BIBLIOGRAPHY	150
	Appendices A - B	159-
		164

LIST OF TABLES

TABLE NO	TITLE	PAGE
3.1	Geometry of the various models	52
3.2	Concrete mechanical and brittle cracking properties used in the FE model (Abdullah R., 2004)	62
3.3	Steel properties (Abdullah R., 2004)	65
3.4	Interfacial layer properties used in the finite element model	66
4.1	Coefficients for conversion of applied load to equivalent uniform load	73

LIST OF FIGURES

FIGURE NO	TITLE	PAGE
1.1	Configuration of a typical steel-concrete composite slab with trapezoidal decking.	2
1.2	Illustration of an open rib type of composite slab.	2
1.3	Typical Trapezoidal and Re-entrant deck profiles.	4
1.4	Examples of trapezoidal deck profiles: (Left side) Up to 60 mm deep; (Right side) Greater than 60 mm deep	5
1.5	Typical forms of interlock in composite slabs	7
2.1	Visualization of general modes of fracture	17
2.2	Steel-concrete composite slab collapse modes.	18
2.3	Application of cohesive zone elements along bulk element boundaries	23
2.4	Cohesive stresses are related to the crack opening width (w).	25
2.5	Variation of cohesive stress with respect to the crack opening displacement in the process zone.	26
2.6	Stress distribution and cohesive crack growth in mode-I opening for concrete.	29
2.7	Forms of the TSL: a) cubic, b) constant, c) Exponential, d) Tri-linear	30
2.8	Debonding damage model	31
2.9	Constitutive strain softening equations	32

2.10	(a) Visualization of the process zone at the crack tip, and definition of displacement jump δ and cohesive tractions t . (b) Example of mode I cohesive law: Rose-Smith-Ferrante universal binding law.	34
2.11	Power law form of the shear retention model.	36
2.12	Mode mix measures based on traction	38
2.13	Linear damage evolution.	39
2.14	Illustration of mixed-mode response in cohesive elements.	40
2.15	Fracture energy as a function of mode mix.	41
2.16	Tensile stress-elongation curves for quasi-brittle material.	43
2.17	FPZ in Quasi-brittle (concrete).	43
2.18	Response of concrete to uniaxial load in tension (a) and compression (b).	44
2.19	Illustration of the definition of the cracking strain ε_t^{ck} used for the definition of tension stiffening data.	46
2.20	Post-failure stress-displacement curve.	47
2.21	Fracture energy illustration.	48
2.22	Definition of the compressive inelastic (or crushing) strain ε_c^{in} used for the definition of compression hardening data.	49
3.1	Geometry of beam corresponding to 3VL16-4-7.5 composite slab.	53
3.2	a) Isometric view of test setup b) Details at supports	54
3.3	Small Scale specimens before concrete casting	55
3.4	Pour stop at the end section of small scale beams	55
3.5	Configuration of the small scale test setup	56
3.6	Picture of a full-scale composite slab specimen	56
3.7	Schematic view of composite slab with trapezoidal decking (VULCRAFT)	57
3.8	Mesh pattern for 3VL16-4-7.5 composite deck slab	57
3.9	Mesh pattern for 3VL16-8-7.5 composite deck slab	58

3.10	Mesh pattern for 3VL16-10-7.5 composite deck slab	58
3.11	Mesh pattern for 3VL16-12-5 composite deck slab	59
3.12	Mesh pattern for 3VL16-14-5 composite deck slab	59
3.13	Typical stress-strain relationship for concrete	61
3.14	Concrete behavior: (a) Tensile; (b) Compressive.	63
3.15	Convergence problem in long span composite slabs.	64
3.16	Typical stress-strain relationship for steel (bi-linear strain hardening)	65
3.17	Horizontal shear bond versus end slip curves for various models	67
3.18	Boundary conditions for 3VL16-4-7.5 composite deck slab	69
3.19	Demonstration of interaction surfaces between rigid body, concrete and neoprene.	69
4.1	Converting the point load in the model to uniform load (Udin, 2006)	71
4.2	Support reaction force or loading force versus time	74
4.3	Mid-span deflection versus time	74
4.4	Support reaction force versus mid-span deflection	75
4.5	Comparison between experimental force-displacement curve and predicted structural response with various smooth factors.	75
4.6	Equivalent uniform load vs. mid-span deflection curve resulted from ABAQUS	76
4.7	Kinetic energy vs. time curves for concrete, interface layer and the whole model.	77
4.8	Internal energy vs. time curves for concrete, interface layer and the whole model	78
4.9	Comparison of kinetic energy and total energy for the whole model	78
4.10	Damage dissipation energy vs. time curves for constituent components and for the whole model.	79
4.11	Determination of critical instances in damage	80

	evolution process of 3VL16-4-7.5 composite slab	
4.12	Damage status in the concrete and in the cohesive interface layer when the mid-span displacement is equal to 2.3mm.	82
4.13	Exhibition of crack development paths in the right side of the small scale beam tested at Virginia Tech (Abdullah, 2004).	82
4.14	Damage status in the concrete and in the cohesive interface layer when the mid-span displacement is equal to 4.9 mm.	83
4.15	Damage status in the concrete and in the cohesive interface layer when the mid-span displacement is equal to 10 mm.	85
4.16	Exhibition of major crack due to slip failure in the left side of the small scale beam tested at Virginia Tech (Abdullah, 2004)	85
4.17	Illustration of Major crack due to slip failure at the right side of the small scale specimen tested at Virginia Tech (Abdullah, 2004)	86
4.18	Depiction of longitudinal end slip resulted from analysis with ABAQUS	86
4.19	Von Mises stress contour in whole of the specimen when time is equal to 0.03 second	87
4.20	(Second picture) Contour of longitudinal shear bond stress along the length of the composite slab when the damage status in the interface layer is exhibited with the first upper picture.	88
4.21	Longitudinal Shear stress vs. time for six random elements as shown in previous figure.	89
4.22	Variation of end slip according to time for 3VL16-4-7.5 composite slab.	89
4.23	Longitudinal Shear bond stress vs. end slip	90
4.24	Contour of displacement in direction 2 for 3VL16-4-	90

	7.5 composite slab with scale factor allocated equal by 3.	
4.25	Picture of end slip for 3VL16-4-7.5 composite slab (Abdullah, 2004)	91
4.26	Support reaction force or applied loading force versus time curve.	92
4.27	Mid-span deflection versus time indicating loading rate.	93
4.28	Support reaction force or applied loading force versus mid-span deflection.	93
4.29	Comparison between experimental force-displacement curve and predicted structural response	94
4.30	Kinetic energy vs. time curves for concrete, interface layer and the whole model.	94
4.31	Internal energy vs. time curves for concrete, interface layer and the whole model.	95
4.32	Comparison of kinetic energy and total energy for the whole model.	96
4.33	Damage dissipation energy vs. time curves for constituent components and for the whole model.	96
4.34	Steps of Damage in Concrete and Interface according to equivalent uniform load graph.	98
4.35	Damage status in the concrete and in the cohesive interface when the mid-span displacement is equal to 8.5 mm.	99
4.36	Crack maps for specimen 3VL16-8-7.5 (Abdullah, 2004)	100
4.37	Exhibition of crack development paths in the left side of the small scale beam tested at Virginia Tech (Abdullah, 2004)	101
4.38	Damage status in the concrete and in the cohesive interface when the mid-span displacement is equal to 24 mm.	102
4.39	Picture of longitudinal displacement of the model	103

	which shows that the red color region near the bottom flange has slipped and displaced to left	
4.40	Von Mises stress contour in whole of the specimen at a certain time.	104
4.41	(Second picture) Contour of longitudinal shear bond stress along the length of the composite slab.	105
4.42	Longitudinal Shear stress vs. time for some random elements as shown in previous figure.	105
4.43	Horizontal shear stress versus end slip	106
4.44	Picture of end slip of 3VL16-8-7.5 composite slab	106
4.45	Contour of displacement in direction 2 for steel decking of 3VL16-8-7.5 composite slab with scale factor	107
4.46	Buckling shape of steel decking at final stages of loading tested at Virginia Tech (Abdullah, 2004).	107
4.47	Support reaction force versus time graph.	108
4.48	Mid-span deflection versus time indicating loading rate.	109
4.49	Support reaction force versus mid-span deflection graph.	109
4.50	Comparison between experimental force-displacement curve and predicted structural response	110
4.51	Kinetic energy vs. time curves for concrete, interface layer and the whole model.	110
4.52	Internal energy vs. time curves for concrete, interface layer and the whole model.	111
4.53	Comparison of kinetic energy and total energy for the whole model.	112
4.54	Damage dissipation energy vs. time curves for concrete, interface layer and the whole model.	112
4.55	Steps of Damage in Concrete and Interface according to applied uniform load vs. mid-span deflection graph.	113

4.56	Damage status in the concrete and in the cohesive interface when the mid-span displacement is equal to 12 mm.	114
4.57	Picture of longitudinal displacement of the model.	115
4.58	Von Mises stress contour in whole of the specimen at a certain time step.	115
4.59	Longitudinal Shear stress vs. time for some random elements at interface layer.	116
4.60	Longitudinal Shear bond stress vs. end slip curve.	116
4.61	Configuration of test set-up for 3VL16-12-5 Composite Slab	117
4.62	Mid-span deflection versus time indicating loading rate.	117
4.63	Support reaction force versus mid-span deflection graph.	118
4.64	Equivalent uniform load vs. mid-span deflection curve resulted from ABAQUS in comparison with experimental tests.	118
4.65	Kinetic energy vs. time curves for concrete, interface layer and the whole model.	119
4.66	Internal energy vs. time curves for concrete, interface layer and the whole model.	120
4.67	Comparison of kinetic energy and total energy for the whole model.	121
4.68	Damage dissipation energy vs. time curves for concrete, interface layer and the whole model.	121
4.69	Steps of Damage in Concrete and Interface according to equivalent uniform load graph.	122
4.70	Damage status in the concrete and in the cohesive interface when the mid-span displacement is equal to 33 mm.	123
4.71	Picture of crack development paths in the concrete body	124

4.72	The cracking pattern matches with numerical analysis results done by ABAQUS software	124
4.73	Picture of longitudinal displacement of the model	125
4.74	Von Mises stress contour in whole of the specimen at a certain time step.	126
4.75	Depiction of some random selected elements for extraction of horizontal shear bond stress vs. time graphs	126
4.76	Longitudinal Shear stress vs. time for some random elements at interface layer.	127
4.77	Horizontal shear bond stress vs. end slip curves	127
4.78	Configuration of test set-up for 3VL16-14-5 Composite Slab	128
4.79	Mid-span deflection versus time indicating loading rate.	129
4.80	Support reaction force versus mid-span deflection graph.	130
4.81	Comparison between experimental force-displacement curve and predicted structural response	130
4.82	Equivalent uniform load vs. mid-span deflection curve resulted from ABAQUS in comparison with experimental tests.	131
4.83	Kinetic energy vs. time curves for concrete, interface layer and the whole model.	131
4.84	Internal energy vs. time curves for concrete, interface layer and the whole model.	132
4.85	Comparison of kinetic energy and total energy for the whole model.	133
4.86	Damage dissipation energy vs. time curves for concrete, interface layer and the whole model.	133
4.87	Steps of Damage in Concrete and Interface according to equivalent uniform load graph.	134
4.88	Damage status in the concrete and in the cohesive	135

	interface when the mid-span displacement is equal to 40 mm.	
4.89	Cracks developed in the laboratorial test of 3VL16-14-5 Composite Slab	136
4.90	Crack maps for specimen 3VL16-14-5 composite slab	136
4.91	Picture of longitudinal displacement of the model.	137
4.92	Von Mises stress contour in whole of the specimen when mid-span deflection is equal to 4cm.	138
4.93	Depiction of some random selected elements for extraction of horizontal shear bond stress vs. time graphs.	138
4.94	Longitudinal Shear stress vs. time for some random elements at interface layer.	139
4.95	Longitudinal Shear bond stress vs. end slip curve.	139
4.96	Picture of end slip for 3VL16-14-5 composite slab (Abdullah, 2004)	140

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Mixed mode fracture	159
B	Comparison between experimental results and numerical results with various smooth factors for various composite slabs.	161

NOMENCLATURES

b	Unit width of slab
d	Midspan displacement
d_d	Depth of profiled steel deck
d_s	Steel deck depth
E	Modulus of elasticity / Young's modulus
E_{11}	Modulus of elasticity in longitudinal direction
E_{22}	Modulus of elasticity in transverse direction (2-axis)
E_{33}	Modulus of elasticity in transverse direction(3-axis)
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel deck
f'_c	Concrete compressive strength
F_y	Minimum yield strength of steel sheeting
F_u	Ultimate strength of steel sheeting
G_{12}	Stiffness modulus in plane 1-2
G_{13}	Stiffness modulus in plane 1-3
G_{23}	Stiffness modulus in plane 2-3
h_c	Concrete cover depth above deck top flange
h_t	Total slab thickness
L	Total slab span
L_s	Shear span
M	Bending moment
P	Point load
t	Steel sheeting thickness
t_c	Concrete thickness

U1	Movement in axis 1
U2	Movement in axis 2
U3	Movement in axis 3
UR1	Rotation movement in axis 1
UR2	Rotation movement in axis 2
UR3	Rotation movement in axis 3
w	Uniform load
ν	Poisson's ratio
δ	Vertical deflection
τ	Shear bond stress

CHAPTER I

INTRODUCTION

1.1 Introduction to Steel-Concrete Composite Slabs

According to the definition made by ASCE (1992) “A composite slab system is one comprising of normal weight or lightweight structural concrete placed permanently over cold-formed steel deck in which the steel deck performs dual roles of acting as a form for the concrete during construction and as positive reinforcement for the slab during service”.

Composite flooring system is essentially consisted of one-way spanning structural components. The slabs span between the secondary floor beams, whereas these secondary beams span transversely between the primary beams.

Cold-formed steel deck composite slab enjoys the optimized interaction and superposition principle of two major engineering materials in an efficient and economic way. Thus this effective and interesting method of composite construction in which the corrugated steel deck acts also as a shear connexion (shear key) has become common nowadays in construction industry providing several pragmatic and economic advantages over other traditional flooring systems.

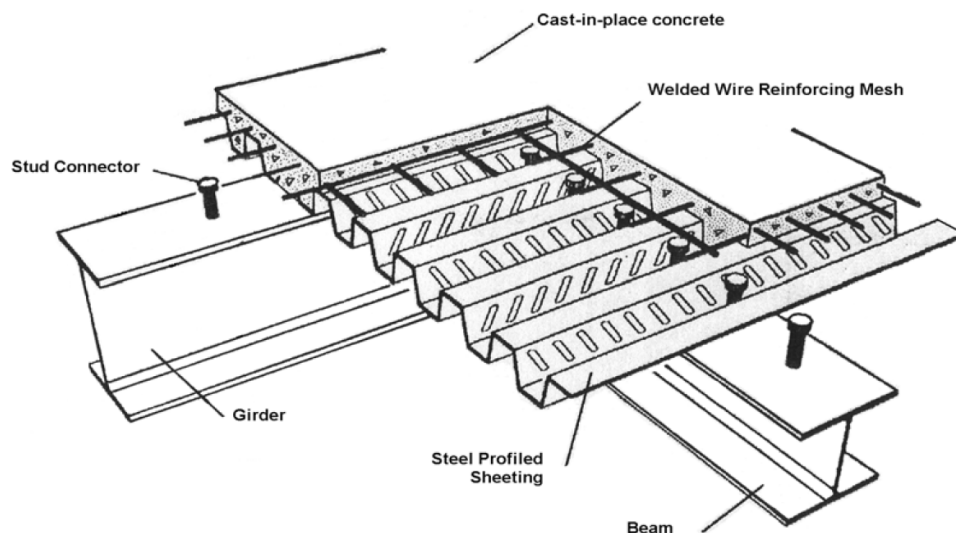


Figure 1.1: Configuration of a typical steel-concrete composite slab with trapezoidal decking (G. Mohan Ganesh *et al.*, 2006).

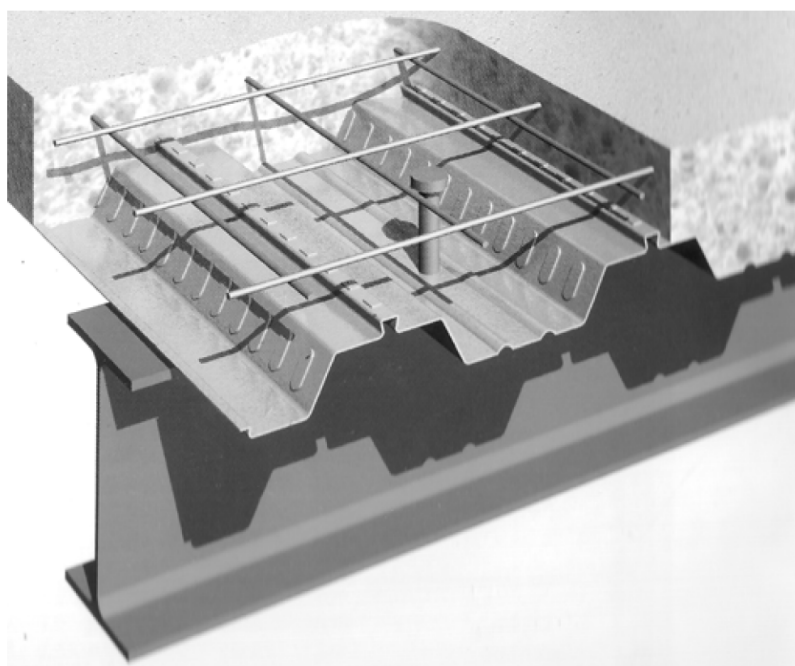


Figure 1.2: Illustration of an open rib type of composite slab (G. Mohan Ganesh *et al.*, 2005).

The structural features and privileges of composite slabs over conventional systems of reinforced concrete slabs which makes them very attractive to structural designers are as follows:

- 1) Speed and simplicity of construction is considerable in this form of construction. This is achievable through separation of professional trades.
- 2) Lighter construction than a traditional concrete building is achievable.
- 3) Less on site construction is required.
- 4) Elimination of scaffolding process is usually possible.
- 5) Strict tolerances achieved by using steel members manufactured under controlled factory conditions to established quality procedures.
- 6) The metal deck acts as positive reinforcement after the concrete sets.
- 7) The metal deck serves as a working platform for the workmen, their tools, materials, and equipment prior to casting the concrete and as a form to support support the wet concrete before hardening of concrete.
- 8) The shape of steel deck leads to a reduced amount of concrete resulting in reduced column sizes and smaller foundation loads.
- 9) Saving in transportation, handling and erection processes because decking is light and is delivered in pre-cut lengths that are tightly packed into bundles.
- 10) Savings in steel weight up to a considerable value in comparison with non-composite construction is possible.
- 11) Structural stability specially in lateral direction improves.
- 12) Structural integrity enhances.
- 13) Shallower construction is attainable with composite slabs. This means, greater stiffness with shallower depth of flooring system is achievable.
- 14) Ease of installation of services is favorable in this kind of construction.

Three generic deck types are commonly available, re-entrant (dovetail), trapezoidal and so-called deep decking as shown in Figures 1.3 and 1.4. Re-entrant and trapezoidal are both 'shallow' decking – typically between 45 and 90mm deep overall, and are used to span between 3 and 4.5m. Deep decking is suitable for spans up to around 9m.

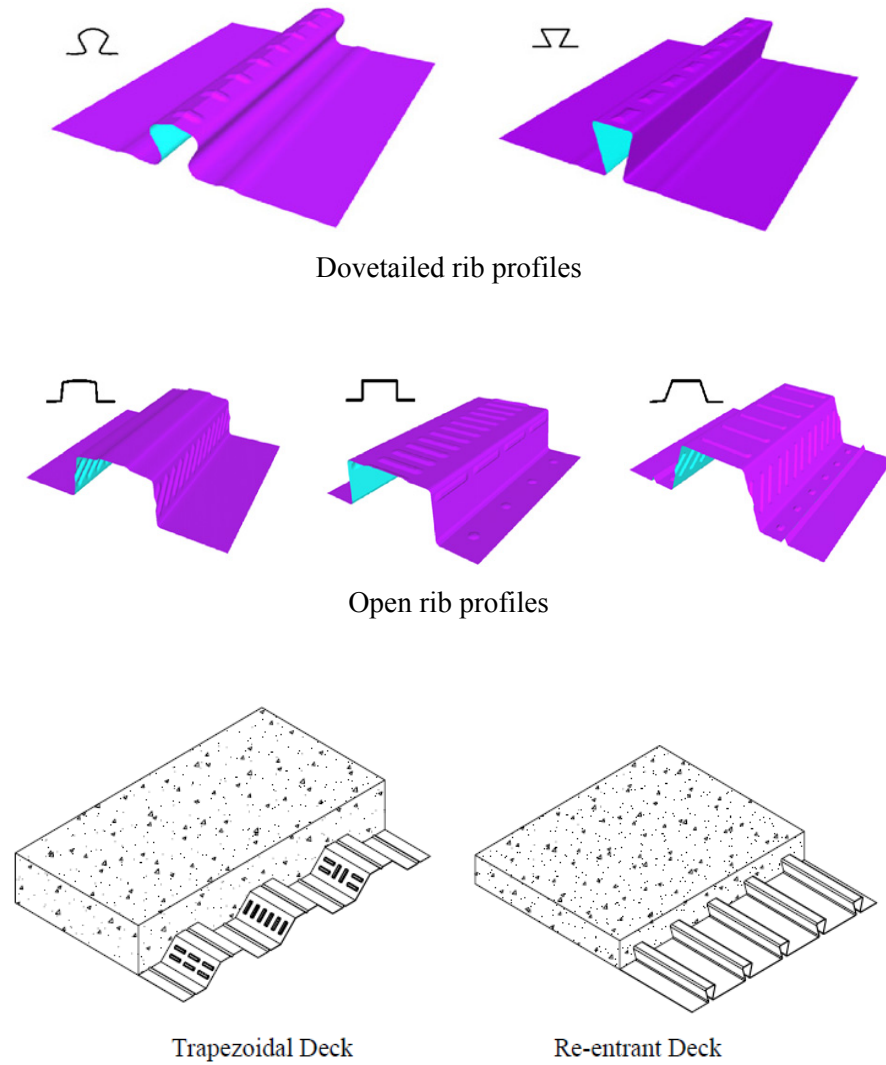


Figure 1.3: Typical Trapezoidal and Re-entrant deck profiles (First two rows: Miquel Ferrer, 2006); (Third row: Thomas Mathew Traver, 2002)

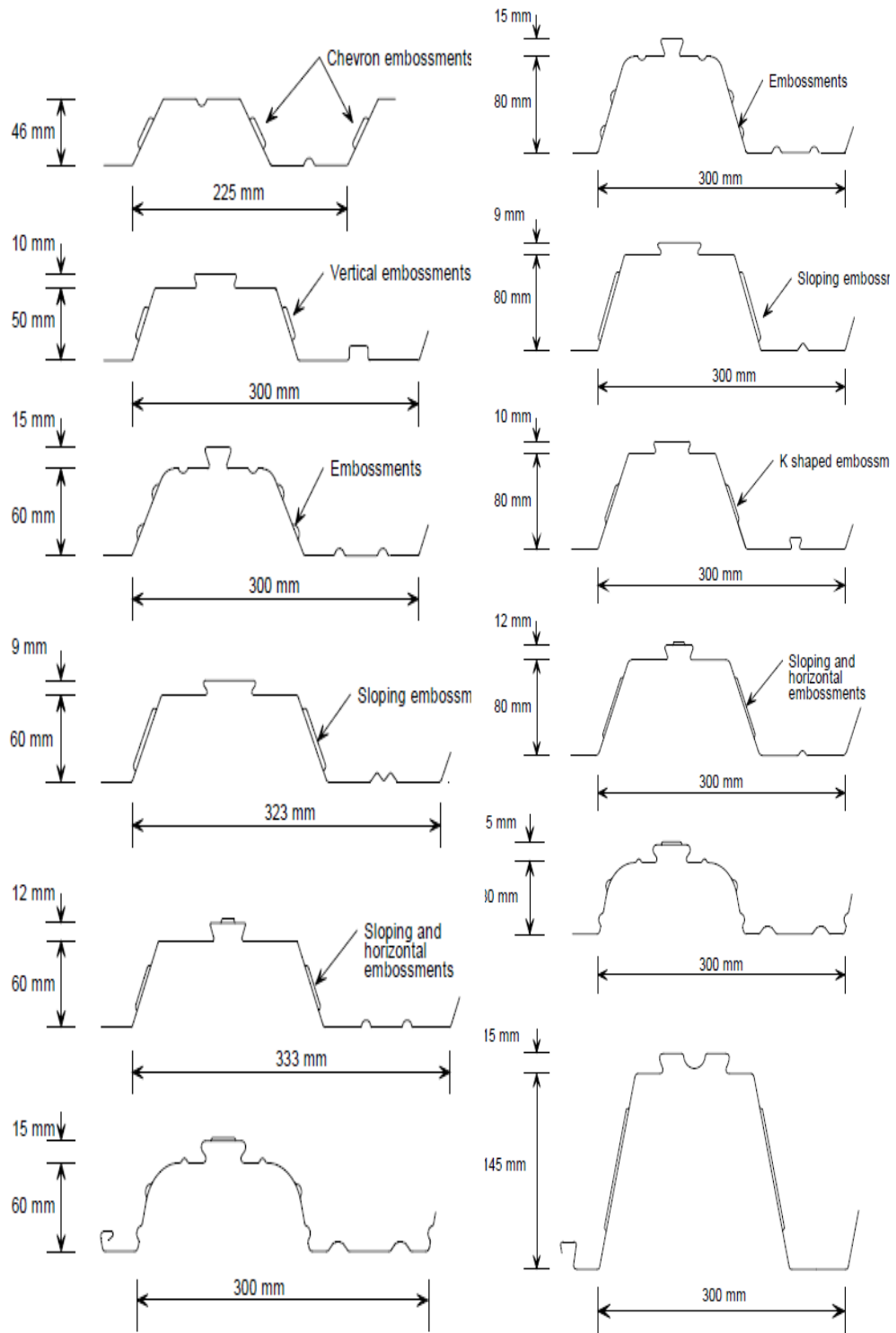


Figure 1.4: Examples of trapezoidal deck profiles: (Left side) Up to 60 mm deep;
 (Right side) Greater than 60 mm deep (J W Rackham *et al.*,
 The Metal Cladding & Roofing Manufacturers Association, 2009)

A composite form deck has two major functionalities which are supporting self weight and the weight of the unhardened concrete, and construction activities because this system is usually constructed without propping. After strength development of concrete up to the designed amount, it will adhere to the steel sheeting firmly and this will unite these two totally different materials to cooperate together in a composite form and to collaborate in load bearing in an efficient way.

It is an established fact that the efficiency of the composite slabs depends on the composite action between the steel and the concrete. In order to achieve the required composite action and to ensure that the steel deck acts as tensile reinforcement, longitudinal shear forces have to be transferred between the steel deck and concrete.

In other words, maintaining composite action requires transfer of load between the concrete and steel. This load transfer is referred to as bond and is idealized as a continuous stress field that develops in the vicinity of the steel-concrete interface.

Apart from horizontal shear forces, the imposed bending action can create vertical separation between the steel and the concrete. Therefore, the profiled sheeting must resist vertical separation as well as transferring of horizontal shear forces at the steel-concrete interfaces.

According to experimental tests, it is known that the shear bond generally breaks down when a 'slip' (relative displacement between the decking and the concrete) of 2 to 3 mm has occurred at the ends of the span of normal composite slab sections. An initial slip, which is associated with the breakdown of the chemical bond, may occur at a lower level of load. The interlock resistance is usually employed by means of the performance of the embossments in the deck (which cause the concrete to 'ride-over' the decking), and the presence of re-entrant parts in the deck profile (which prevent the separation of the deck and the concrete).

Therefore the profiled sheeting should be able to transfer longitudinal shear to concrete through the interface to ensure composite action of the composite slab. The adhesion between the steel profile and concrete is generally not sufficient to create

composite action in the slab and thus an efficient connection is achieved with one or several of the following methods (Figure 1.5) :

- a) Appropriate profiled decking shape (re-entrant or open trough profile), which can affect shear transfer by frictional interlock;
- b) Mechanical anchorage provided by local deformations (indentations or embossments) on the surface of decking;
- c) Holes or incomplete perforation on the surface of steel sheeting;
- d) End anchorage induced by means of welded studs or other forms of local connection between the concrete and the steel decking;
- e) End anchorage by deforming the ribs shape at the end of the steel decking.

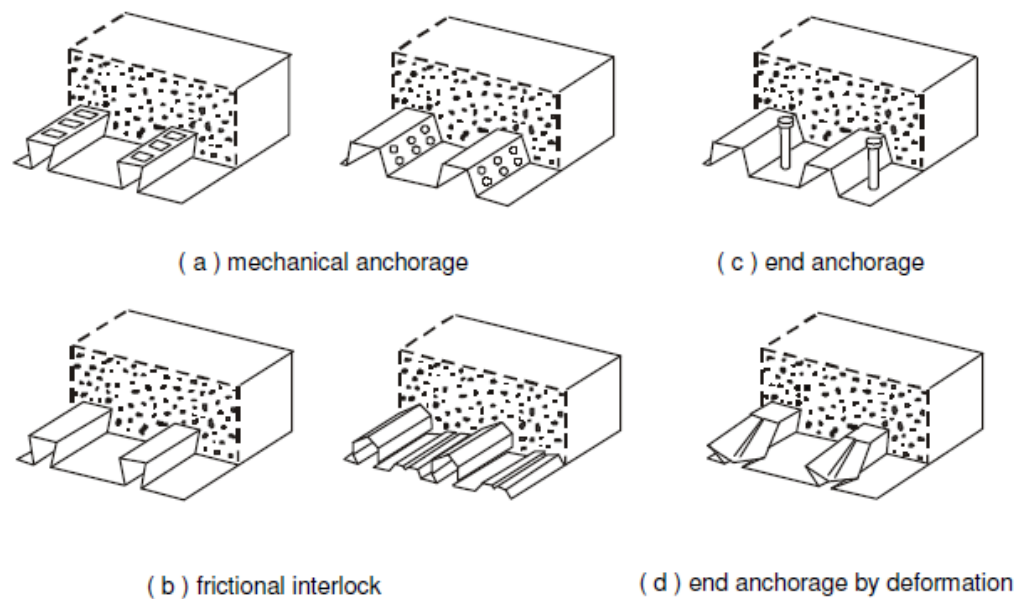


Figure 1.5: Typical forms of interlock in composite slabs (Eurocode4, 2001; Abera Dugassa, 2005)

It must be mentioned that the spacing of the supporting beams, and hence the span of slab is dependent on the procedure of construction. If the beam spacing was less than 3.5m, then no temporary shoring is vital during construction period. This means that the construction stage governs the design of the steel sheeting. Because of the shortness of the slab span, the stresses that will develop in the composite slab

after hardening of overtopping concrete are not too much or critical. Therefore, trapezoidal metal decking which have low horizontal shear resistance and ductility and also have the smallest steel weight per square meter of floor area, are suitable for short span slabs. For other flooring layouts which the beams are spaced at larger distances, shoring is necessary to support the steel decking during concreting stage. Because of the longer slab span, the final state stress that will develop in composite slab is much more greater. This critical stress will govern the design of such long composite slabs. In order to establish required high stress transference between steel and concrete, the steel deckings with high amount of engagement will be employed. Dovetailed profiles which induce frictional engagement of steel and concrete are usually utilized in such cases although they give into hand higher steel weight per square meter of floor area. But they can properly develop horizontal shear resistance which is essential for long span composite slabs.

1.2 Problem Statement

The structural interaction of concrete slab and steel deck materials in an optimized manner provides an extremely efficient and economical engineering solution for flooring systems.

The rapidly increasing adoption of such flooring systems in practice has resulted in an intensification of the supporting research effort for evaluation and investigation of their structural performance.

As far as we are concerned about the study of structural and mechanical behavior of such a system, the investigation of its major controlling modes of failure is inevitable for more actual modeling of performance of composite slabs.

The strength of the composite diaphragms is majorly influenced by one of the three limit states, diagonal tension failure of the concrete slab, edge connector failure (shear stud damage) or shear transfer mechanism failure which result from

separation of interconnected layers and slippage of the these two neighboring layers of concrete mass and steel decking.

The shear bond interaction at the interface of steel deck and concrete can be separated into three distinctive components, namely, the chemical bonding, mechanical interlocking, and friction between the two materials. The first component is the type of bond that is developed through a chemical process as the concrete cured or hardened. This component of interaction is brittle in nature, and once it is broken it can not be restored. The mechanical interlocking attains its strength from the interlocking action between the concrete and the steel decking due to the presence of embossments or indentations. This action is directly controlled by the embossment shape and steel deck thickness. Finally, the presence of the friction between the concrete and the steel deck is due to the presence of internal pressure between the two materials.

If the connection between the concrete and steel sheet is perfect, that is if longitudinal deformations are equal in the steel sheet and in the adjacent concrete, the connection provides complete interaction (perfect bond or perfobond). If a relative longitudinal displacement exists between the steel sheet and the adjacent concrete, the slab has incomplete interaction. The difference between the steel and adjacent concrete longitudinal displacement can be characterized by the relative displacement called slip.

It is desirable to take into account the fracture mechanisms of the body of concrete considering the first and second modes of failure (opening and shear modes) and also the failure mode concerning to shear bond breakage mechanism (slip or uplift in steel-concrete contact surface). Investigation of the effect of relative displacement between the concrete and steel decking which can bring the composite slab to nonlinear response is the major purpose of this study.

It is an established fact that the interaction between the composite interfaces is very intricate because stresses and strains in the contact zone between the profiled metal sheeting and the concrete are complex and depend on many factors.

The analysis and design procedures available nowadays must rely inevitably on experimental data results to account for the concrete-steel interaction parameters since the bondage between this two totally different layers arises through some completely various range of processes which can be classified as mechanical, frictional and chemical bond.

Modeling the actual behavior and performance of shear bond considering various modes of failure of slab is a pivotal issue and plays a major role in numerical study of composite action criterion.

Previous experimental investigations provide data for development, calibration and verification of a model to represent load transfer between reinforcing steel and concrete. The results of previous analytical investigations provide insight into model development and implementation within the framework of the finite element method.

1.3 Aim of Study

Motivations for conducting this research study are as follows:

- a) To develop a numerical model that incorporates the precise discontinuous material behavior and allows for the effects of debonding (horizontal slip and vertical separation) between the concrete and steel decking.
- b) To establish and demonstrate a reliable, and accurate methodology for numerical analysis of steel-concrete composite slabs.

1.4 Objectives of Study

The objectives of the study can be summarized as follows:

- a) To develop the nonlinear FE model with damage based mechanics for composite slabs under flexural loading using cohesive element to simulate the interaction between concrete and steel deck and to simulate the cracking of plain concrete considering mixed modes of fracture by means of concrete damaged plasticity available in ABAQUS software.
- b) To perform the quasi-static analysis through explicit dynamics procedure for the models for simulation and determination of the actual behavior of composite slab.
- c) To evaluate mechanisms of damage, step by step in VULCRAFT steel-concrete composite slabs when damage initiates and to investigate its propagation regime.
- d) To validate the applicability of the proposed model by comparing the predicted behaviors with those observed in experimental results obtained by research work performed at Virginia Tech (Abdullah,2004).

1.5 Scopes of Study

The scopes of works for this research and the restrictions and assumptions are categorized as follows:

- a) The FE model has been developed in 3-D space.
- b) This study assumes that steel sheeting is plane and smooth surface without any indentation or embossment or dimples or welded wire meshing to deck or any other mechanical interlocking bonds.
- c) It has been assumed that not any stud shear connector or steel dowel is employed in the region of supporting beam hence composite slab span is totally simply supported.
- d) Configuration of empirical data used in this study follows exactly the experimental works setup carried out by Abdullah (2004).
- e) The analyses are just performed for trapezoidal shape cold-formed steel decks manufactured by Vulcraft of Nucor Research and Development, USA.

BIBLIOGRAPHY

Abdollahi A. Numerical strategies in the application of the FEM to RC structures-I. Computers and Structures 1996;58(6):1171–82.

Abdullah, R. and Easterling, W.S. (2003) Structural evaluation of new VULCRAFT composite deck profile: Phase II, Report No. CEE/VPI-ST03/01, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

An, L. (1993). "Load Bearing Capacity and Behaviour of Composite Slabs with Profiled Steel Sheet," Ph.D Dissertation, Chalmers University of Technology, Sweden.

ANSYS Software Documentations; version 11, United States of America.

Bazant ZP, Kim S-S (1979). Plastic fracturing theory for concrete. Journal of Engineering Mechanics Div (ASCE); 105(3):407–28.

Bode, H., and Sauerborn, I. (1992). “ Modern Design Concept for Composite Slabs with Ductile Behaviour.” Proceedings of an Engineering Foundation Conference on Composite Construction in Steel and Concrete 1992, American Society of Civil Engineers, 125-141.

Bode H, Minas F (1997). Composite slabs with and without end anchorage under static and dynamic loading. In: Proceedings of engineering conference composite construction—conventional and innovative.

Bode H, Minas F, Sauerborn I (1996). Partial connection design of composite slabs. *Journal of Structural Engineering International*; 6(1):53–6.

Calixto JM, Lavall AC, et al (1998). Behaviour and strength of composite slabs with ribbed decking. *Journal of Constructional Steel Research*; 46(1–3):211–2.

Crisinel M, Ferrer M, Marimon F, Rossich Verdes M, (2006). Influence of sheet surface conditions and concrete strength on the longitudinal shear resistance of composite slabs. In: Prof. J.-M. Aribert retirement symposium proceedings, INSA, Rennes, 3–5 July 2006.

Crisine, M., Daniels, B. and Ren, P. (1992). “Numerical Analysis of Composite Slab Behavior,” *Proceedings of an Engineering Foundation Conference on Composite Construction in Steel and Concrete II*, ASCE, June, pp. 798-808.

CSSBI. (1996) *Standard for Composite Steel Deck*, CSSBI 12M - 96, Canadian Sheet Steel Building Institute.

Daniels, B. J., and Crisinel, M. (1993). “Composite Slab Behavior and Strength Analysis. Part I: Calculation Procedure.” *Journal of Structural Engineering*, 119(1-4), 16-35.

Daniels, B. J., and Crisinel, M. (1993b). “Composite Slab Behavior and Strength Analysis. Part II: Comparison With Test Results And Parametric Analysis.” *Journal of Structural Engineering*, 119(1-4), 36-49.

De Andrade SAL, da S Vellasco PCG, da Silva JGS, Takey TH. Standardized composite slab systems for building constructions. *Journal of Constructional Steel Research* 2004;60:493–524.

Easterling, W. S., and Young, C. S., (1992). "Strength of Composite Slabs." *Journal of Structural Engineering*, 118(9), 2370-2389.

EN 1993-1-3, Eurocode 3-Part 1.3. Design of steel structures: supplementary rules for cold-formed thin gauge members and sheeting. European Committee for Standardisation, 1996.

Evans HR, Wright HD. Steel–concrete composite flooring deck structures. In: Narayanan R, editor. Steel–concrete composite structures, stability and strength. London: Elsevier Applied Science; 1988. p. 21–52.

Feenstra, P.H. and Borst, R.D., 1996. “A composite plasticity model for concrete”. *Int. J. of Solids and Struct.*, 33(5), 707-730.

Ferrer M, Marimon F, Roure F, Crisinel M. Optimised design of a new profiled steel sheet for composite slabs using 3d non-linear finite elements. In: Proceedings of the 4th European Eurosteel conference on steel and composite structures, Maastricht, 8–10 June 2005.

Ferrer M, Marimon F, Roure F. Design methodology of profiled steel sheets for composite slabs by FEM. European Action COST C12: improving buildings’ structural quality by new technologies. In: Proceedings of the international conference, Innsbruck, 20th–22 January 2005.

Ferrer M (2006), Numerical and experimental approach to the interaction between steel sheet and concrete to improve shear resistance of composite slabs. Doctoral thesis. Technical University of Catalonia (UPC). Barcelona.

F.H.Wittmann (1993), Numerical Models in Fracture Mechanics of Concrete, Swiss Federal Institute of Technology, Zurich.

Goodman JR, Popov P. (1968) Layered beam systems with interlayer slip. *Journal of the Structural Division*; 2535–47.

Hoffmeister, B. and Sedlacek, G. (1996). “Plastic Hinge Theory for Composite Floors and Frames,” Proceedings of the Engineering Foundation Conference on Composite Construction in Steel and Concrete III, ASCE, pp. 887-897.

Izzuddin B. A., Tao X. Y. and Elghazouli, A. Y. (2004). "Realistic Modeling of Composite and Reinforced Concrete Floor Slabs under Extreme Loading I: Analytical Method." *Journal of Structural Engineering*, 130(12), 1972-1984.

J W Rackham et al (2009)., *The Metal Cladding & Roofing Manufacturers Association, Composite Slabs and Beams using Steel Decking: Best Practice for Design and Construction (Revised Edition)*, MCRMA Technical Paper No. 13 SCI Publication No. P300.

Jeong YJ (2005), *Partial-interactive behaviors of steel–concrete composite bridge deck*. Ph.D. Thesis. Korea: Yonsei University.

Johnson, R. P. (1994). *Composite Structures of Steel and Concrete, Vol. 1: Beams, Slabs, Columns, and Frames for Buildings*, Blackwell Scientific Publication, Oxford.

Juožas Valivonis (2006), "Analysis of behaviour of contact between the profiled steel sheeting and the concrete", *Journal of civil engineering and management*.

Kitoh, H. and Sonoda, K. (1996). "Bond Characteristics of Embossed Steel Elements," *Proceedings of the Engineering Foundation Conference on Composite Construction in Steel and Concrete III*, ASCE, pp. 909-918.

Luttrell, L. D. (1987). "Flexural Strength of Composite Slabs" *Composite Steel Structures-Advances, Design and Construction*, Narayanan, R., Ed., Elsevier, London, 106-115.

Makelainen P, Sun Y (1999). The longitudinal behaviour of a new steel sheeting profile for composite floor slabs. *Journal of Constructional Steel Research*;49:117–28.

Marčiukaitis G, Valivonis J, Vaškevičius A (2001). Analysis of behaviour of composite elements with corrugated steel sheeting. *Civil Engineering (Statyba)*;7(6):425–32.

Marčiukaitis G, Jonaitis B, Valivonis J (2006). Analysis of deflections of composite slabs with profiled sheeting up to the ultimate moment. *Journal of Constructional Steel Research*; 62:820–30.

Menrath H, Haufe A, Ramm E (1998). A model for composite steel-concrete structures. In: de Borst R, Bicanic N, Mang H, Meschke G, editors. *Proceedings to the EURO-C*. Rotterdam: Balkema; 1998. p. 33–42.

Nik Mat Bin Udin (2006). *Modeling of Shear Bond in Composite Slab Using Interface Element*. B.Eng. Thesis. University of Technology Malaysia.

Ong, K.C. and Mansur, M.A. (1986). "Shear-Bond Capacity of Composite Slabs Made with Profiled Sheeting," *The International Journal of Cement Composites and Lightweight Concrete*, Vol. 8, No. 4, pp. 231-237.

Patrick, M., and Bridge, R. Q. (1992). "Design of Composite Slabs for Vertical Shear." *Proceedings of an Engineering Foundation Conference on Composite Construction in Steel and Concrete II*, American Society of Civil Engineer, 304-322.

Patrick, M. (1990). "Long-Spanning Composite Members with Steel Decking," *Proceedings of the Tenth International Specialty Conference on Cold-Formed Steel Structures*, University of Missouri- Rolla, pp. 81-102.

Phuvoravan K. and Sotelino E. D. (2005). "Nonlinear Finite Element for Reinforced Concrete Slabs." *Journal of Structural Engineering*, 131(4), 643-649.

Pi YL, Bradford MA, Uy B (2006). Second order nonlinear inelastic analysis of composite steel–concrete members. II: Applications. *Journal of Structural Engineering*, ASCE;132(5):762–71.

Poh, K. W. and Attard, M. M. (1993). "Calculating the Load-Deflection Behaviour of Simply- Supported Composite Slabs with Interface Slip," *Engineering Structures*, Vol. 15, No. 5, pp. 359-367.

Porter ML, Ekberg CE(1976); Design recommendations for steel deck floor slabs. *Journal of the Structural Division, ASCE*;102(ST 11): 2121–35.

Porter ML, Ekberg CE, Greimann LF, Elleby HA (1976). Shear bond analysis of steel deck reinforced slabs. *Journal of the Structural Division, ASCE*;102(ST 12):2255–68.

Porter ML, Ekberg Jr CE. (1971) Investigation of cold-formed steel-deck reinforced concrete floor slabs. In: Yu W-W, editor. First specialty conference on cold-formed steel structures. Rolla: University of Missouri-Rolla; p. 179–85.

Porter, M. L., and Ekberg, C. E. (1977). "Behavior of Steel-Deck-Reinforced Slabs." *Journal of the Structural Division, Volume 103, No. 3, March 1977, 663-677.*

Porter, M. L. and Greimann, L. F. (1984). "Shear-Bond Strength of Studded Steel Deck Slabs," *Proceedings of the Seventh International Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, pp. 285-306.*

Roeder, C. W. (1981). "Point Loads on Composite Deck-Reinforced Slabs," *ASCE Journal of the Structural Division, Vol. 107, pp. 2421-2429.*

Rondal J, Moutafidou A. (1997) Study of shear bond in steel composite slabs. In: *Proceedings of engineering conference—composite construction —conventional and innovative.*

Schuster RM. (1972). Composite steel-deck-reinforced concrete systems failing in shear-bond. Preliminary Report ninth Congress IABSE Amsterdam. Zurich: IABSE.

Schuster, R. M. (1970). "Strength and Behavior of Cold-Rolled Steel-Deck-Reinforced Concrete Floor Slabs," Phd Dissertation, Iowa State University, Ames, Iowa.

Schuster, R. M. and Ling, W.C. (1980). "Mechanical Interlocking Capacity of Composite Slabs," Proceedings of the Fifth International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, pp. 387-407.

Schuurman RG (2001). The physical behaviour of shear connections in composite slabs. Doctoral thesis. Technische Universiteit Delft. DUP Science, Delft.

Schuurman, R. G. and Stark, J.W.B. (1996). "Longitudinal Shear Resistance of Composite Slabs – To a Better Understanding of the Physical Behaviour" Proceedings of the Engineering Foundation Conference on Composite Construction in Steel and Concrete III, ASCE, pp. 89-103.

Sebastian, W. M., and McConnel, R. E. (2000). "Nonlinear FE Analysis of Steel-Concrete Composite Structures". Journal of Structural Engineering. 126(6): 662-674.

Seleim, S. S., and Schuster, R. M. (1985). "Shear-Bond Resistance of Composite Deck- Slabs." Canadian Journal of Civil Engineering, 12(316-323).

Shanmugam, N. E. (2002), Finite element modeling of double skin composite slabs. Department of Civil Engineering, National University of Singapore, Singapore.

Shanmugam, N.E., Kumar G. and Thevendran V. (2002). "Finite element modeling of double skin composite slabs". Finite elements in analysis and Design. 38, 579-599.

Soh CK, Chiew SP, Dong YX (2002). Concrete–steel bond under repeated loading. Magazine of Concrete Research; 54(1):35–46.

Soh CK, Chiew SP, Dong YX (1999). Damage model for concrete–steel interface. Journal of Engineering Mechanics ASCE; 125(8):979–83.

Stark, J. (1978). "Design of Composite Floors with Profiled Steel Sheet," Forth International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, pp. 893-922.

Tenhovuori A, Karkkainen K, Kanerva P. (1996) Parameters and definitions for classifying the behaviour of composite slabs. In: Proceedings of an engineering foundation conference—composite construction in steel and concrete..

Tenhovuori AI, Leskela MV. (1998) Longitudinal shear resistance of composite slab. *Journal of Constructional Steel Research*; 46(1–3):228.

Terry, A.S. (1994). The Effects of Typical Construction Details on the Strength of Composite Slabs, M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Veljkovic, M. (1994) Interaction between Concrete and Sheeting in Composite Slabs. S-971 87 LULEA, Lulea University of Technology, Division of Steel Structures, Lulea, Sweden.

Veljkovic, M. (2000). "Behavior and Design of Shallow Composite Slab," Draft for the Proceedings of an Engineering Foundation Conference on Composite Construction in Steel and Concrete IV, ASCE

Veljkovic, M. (1995). "Longitudinal Shear Capacity of Composite Slabs." Nordic Steel Construction Conference '95, Malmo, Sweden.

Veljkovic, M. (1996a). "Behaviour and Resistance of Composite Slabs," Phd Thesis, Lulea University of Technology, Lulea, Sweden.

Veljkovic, M. (1994). "3-D Nonlinear Analysis of Composite Slabs," DIANA Computational Mechanics '94, Eds: G.M.A. Kusters, M. A. N. Hendricks, pp. 394-404.

Widjaja, B.R. and Easterling, W. S. (1996). "Strength and Stiffness Calculation Procedures for Composite Slabs," 13th International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, pp. 389-401.

Yam, Lloyd C. P. (1981). "Design of Composite Steel-Concrete Structures" Surrey University Press, London.

Yazdani S, Schreyer HL. (1990) Combined plasticity and damage mechanics model for plain concrete. *J Engineering Mechanics (ASCE)*; 116(7):1435–50.

Young, C.S. (1990). Effects of End Restraint on Steel Deck Reinforced Concrete Floor Systems, M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.