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

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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 geraf tegasan ricih mengufuk lawan gelangsaran hujung yang diambil daripada ujian lenturan bersaiz kecil. Model analisis yang dicadangkan dalam kajian ini disahkan kejituannya dengan mebuat 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.

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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 longitudinl 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
υ	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 flooringg systems.

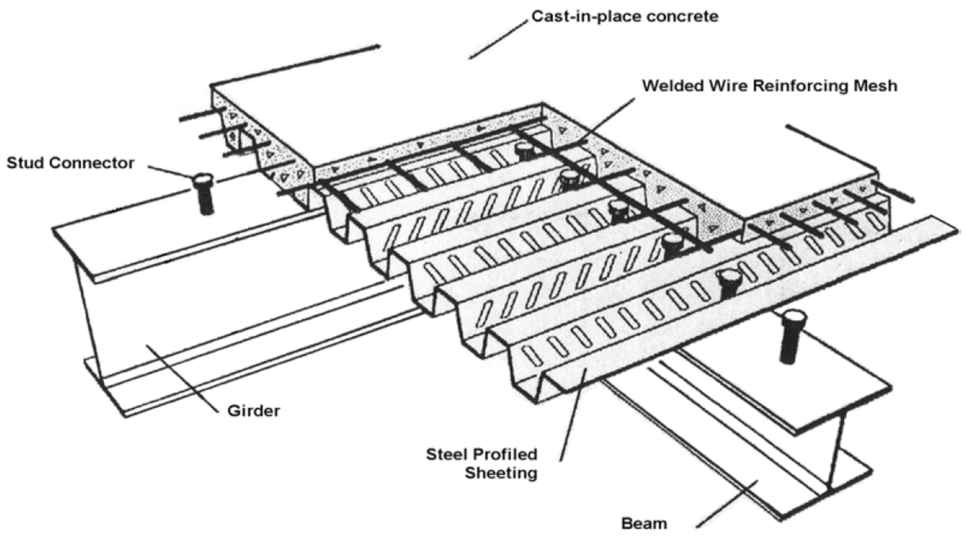


Figure 1.1: Configuration of a typical steel-concrete composite slab with trapezoidal decking (G. Mohan Ganesh *et al.*, 2006).

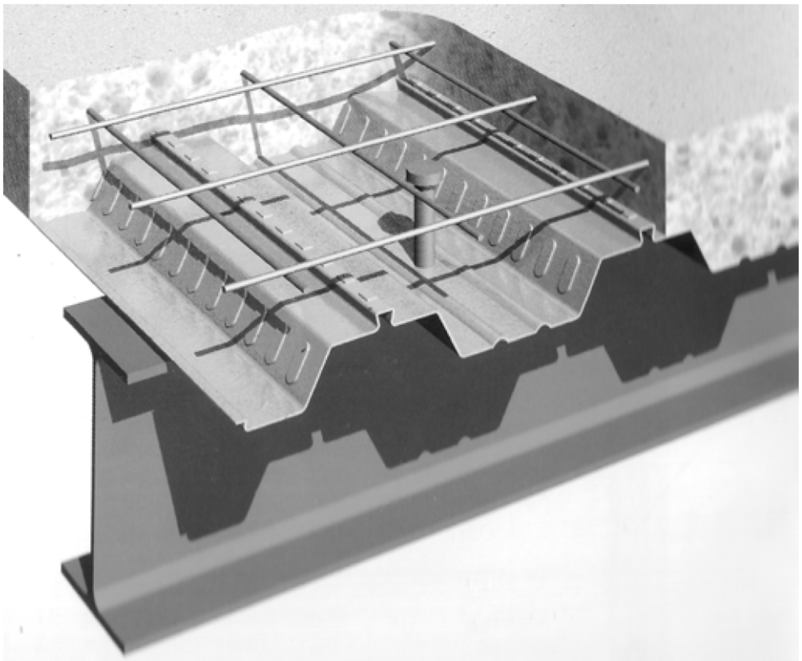


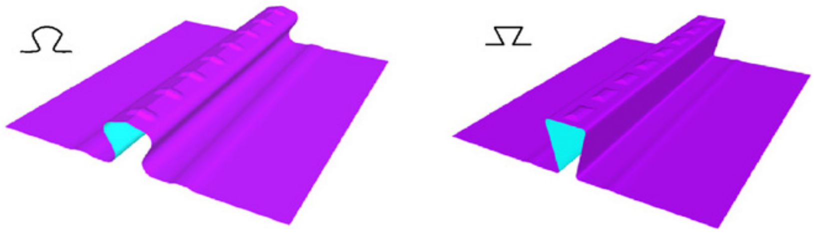
Figure 1.2: Illustration of an open rib type of composite slab (G. Mohan Ganesh *et al.*, 2005).

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:

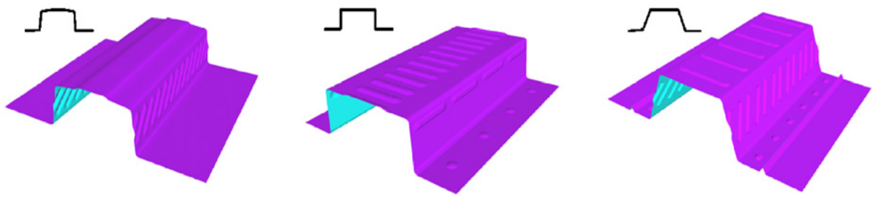
1) Speed and simplicity of construction is considerable in this form of construction. This is achievable through separation of professional trades.
2) Lighter construction than a traditional concrete building is achievable.
3) Less on site construction is required.
4) Elimination of scaffolding process 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.

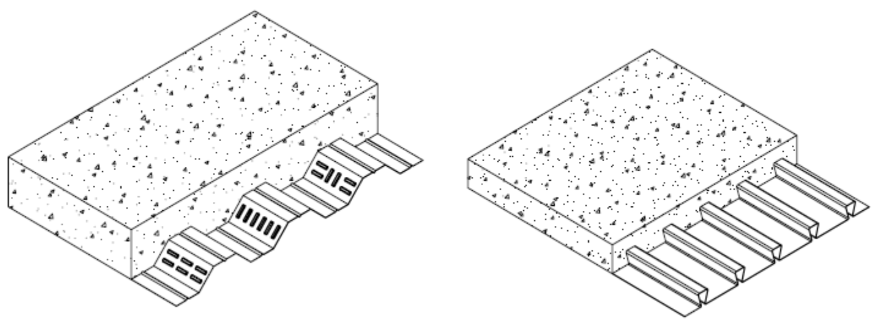
Three generic deck types are commonly available, re-entrant (dovetail), trapezoidal and so-called deep decking as shown in Figures 1.3 and 1.4. Re-entrant and trapezoidal are both ‘shallow’ decking – typically between 45 and 90mm deep overall, and are used to span between 3 and 4.5m. Deep decking is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



Dovetailed rib profiles



Open rib profiles



Trapezoidal Deck Re-entrant Deck

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

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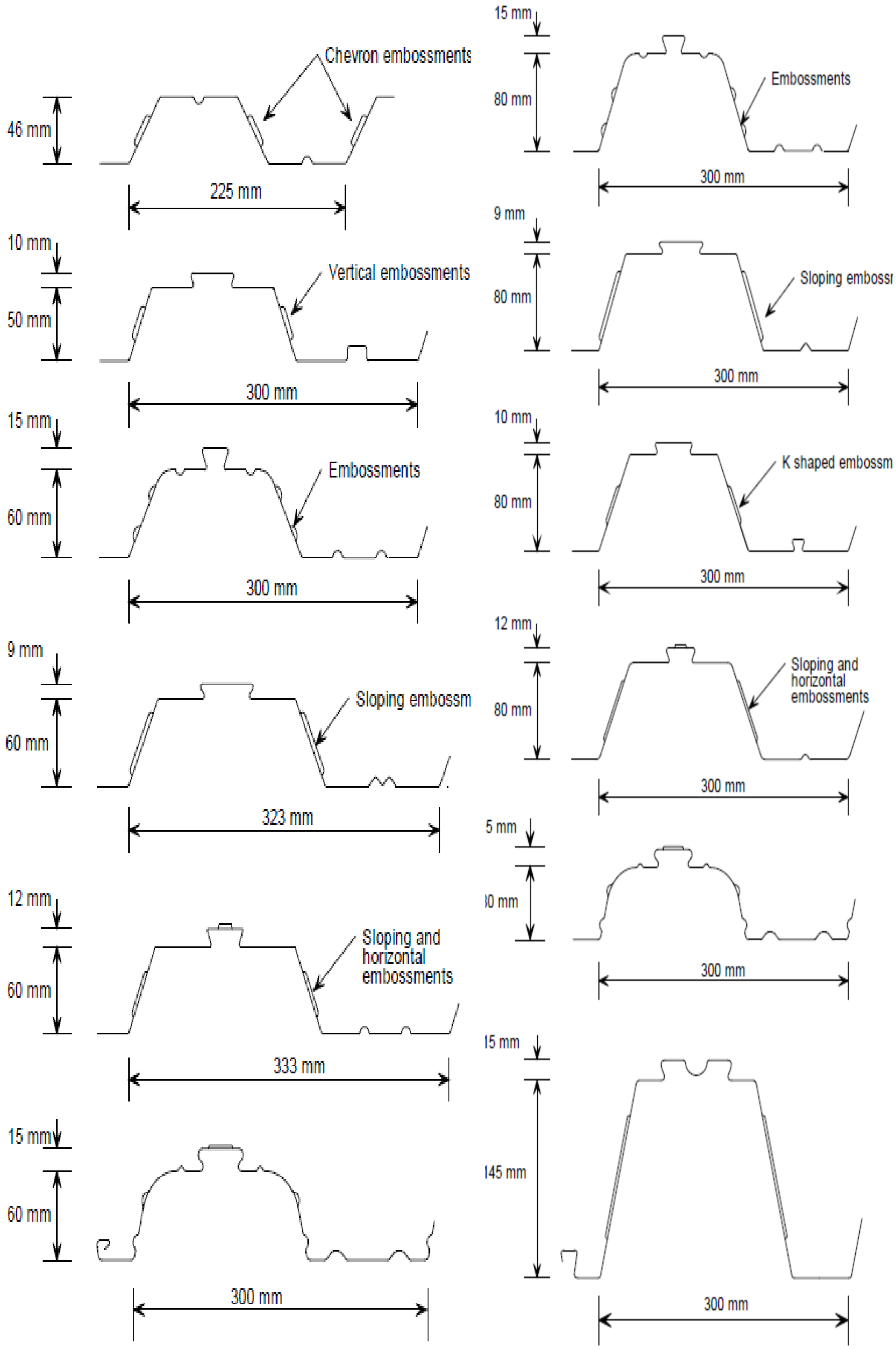

Figure 1.4: Examples of trapezoidal deck profiles: (Left side) Up to 60 mm deep; (Right side) Greater than 60 mm deep (J W Rackham *et al.*, The Metal Cladding & Roofing Manufacturers Association, 2009)

A composite form deck has two major functionality which are supporting self weight and the weight of the unhardened concrete, and construction activites 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 this two totally different material 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 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 o 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.

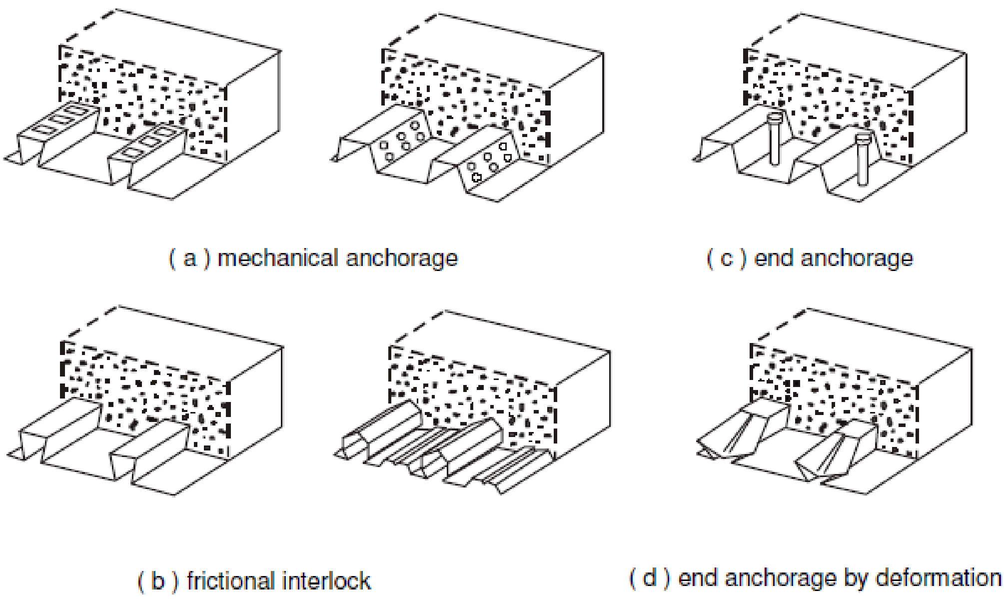

Figure 1.5: Typical forms of interlock in composite slabs (Eurocode4, 2001; Abera Dugassa, 2005)

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 costruction 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 the 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 bobd 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.

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