ANALYSIS AND DESIGN OF
STEEL DECK – CONCRETE COMPOSITE SLABS

Budi Ryanto Widjaja

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY
in
Civil Engineering

W. S. Easterling, Chairman
R. M. Barker
E. G. Henneke
S. M. Holzer
T. M. Murray

October, 1997
Blacksburg, Virginia

Keywords: composite slabs, direct method, iterative method, finite element model, long span, resistance factor
ANALYSIS AND DESIGN OF STEEL DECK – CONCRETE COMPOSITE SLABS

by

Budi R. Widjaja
Dr. W. S. Easterling, Chairman
Department of Civil Engineering

(ABSTRACT)

As cold-formed steel decks are used in virtually every steel-framed structure for composite slab systems, efforts to develop more efficient composite floor systems continues. Efficient composite floor systems can be obtained by optimally utilizing the materials, which includes the possibility of developing long span composite slab systems. For this purpose, new deck profiles that can have a longer span and better interaction with the concrete slab are investigated.

Two new mechanical based methods for predicting composite slab strength and behavior are introduced. They are referred to as the iterative and direct methods. These methods, which accurately account for the contribution of parameters affecting the composite action, are used to predict the strength and behavior of composite slabs. Application of the methods in the analytical and experimental study of strength and behavior of composite slabs in general reveals that more accurate predictions are obtained by these methods compared to those of a modified version of the Steel Deck Institute method (SDI-M). A nonlinear finite element model is also developed to provide additional reference. These methods, which are supported by elemental tests of shear bond and end anchorages, offer an alternative solution to performing a large number of full-scale tests as required for the traditional m-k method. Results from 27 composite slab tests are compared with the analytical methods.

Four long span composite slab specimens of 20 ft span length, using two different types of deck profiles, were built and tested experimentally. Without significantly increasing the slab depth and weight compared to those of composite slabs with typical span, it was found that these long span slabs showed good performance under the load tests. Some problems with the
vibration behavior were encountered, which are thought to be due to the relatively thin layer of concrete cover above the deck rib. Further study on the use of deeper concrete cover to improve the vibrational behavior is suggested.

Finally, resistance factors based on the AISI-LRFD approach were established. The resistance factors for flexural design of composite slab systems were found to be $\phi=0.90$ for the SDI-M method and $\phi=0.85$ for the direct method.
In Memory of my Father
and
In Love of my Mother
ACKNOWLEDGMENTS

I am most grateful to Dr. W. Samuel Easterling for his continuous support, guidance and friendship throughout my graduate study at Virginia Polytechnic Institute and State University (Virginia Tech). I would also like to express my sincere appreciation to the members of the research committee, Dr. R. M. Barker, Dr. E. G. Henneke, Dr. S. M. Holzer and Dr. T. M. Murray. Special thanks goes to Dr. R. M. Barker for his valuable discussion on the resistance factors and to Dr. T. M. Murray for his valuable discussion on floor vibrations.

I gratefully acknowledge financial support from the National Science Foundation, under research grant no. MSS-9222064, the American Institute of Steel Construction, the American Iron and Steel Institute, Vulcraft and Consolidated System Incorporated. Further, material for test specimens was supplied by BHP of America, TRW Nelson Stud Welding Division and United Steel Deck. My sincere thanks is also for the Steel Deck Institute for the Scholarship Award that I received for my research and very special thanks to Mr. and Mrs. R. B. Heagler for their very warm hospitality during my visit at the SDI annual meeting in Florida. Mr. Heagler also keeps me updated with new technical issues and developments in the SDI.

I would also like to thank to Dr. M. Crisinel and Dr. B. J. Daniels for the access to use the COMPCAL program at the Ecole Polytechnique Federale de Lausanne, Switzerland. They also allowed me to use the drawings for the elemental tests.

To all my friends in the Civil Engineering Department and especially those at the Structures and Materials Laboratory of Virginia Tech, I extend my appreciation for their support, discussion and friendship. I am particularly indebted to Joseph N. Howard for his immeasurable help in performing the vibration tests on the long span slabs. Special thanks goes to Dennis W. Huffman and Brett N. Farmer for their constant help and cheerful support during my research work at the Structures Lab.

Last but certainly not the least, I am thankful to my wife, Surjani, for being a constant source of inspiration and encouragement. She is a wonderful wife and friend.
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... ii  
DEDICATIONS ....................................................................................................................................... iv  
ACKNOWLEDGMENTS .......................................................................................................................... v  
TABLE OF CONTENTS ..................................................................................................................... vi  
LIST OF FIGURES .............................................................................................................................. ix  
LIST OF TABLES ............................................................................................................................... xi  
LIST OF NOTATIONS ......................................................................................................................... xii

## Chapter 1. Introduction

1.1. Motivation and Scope of the Research ....................................................................................... 1  
1.2. Organization of this Report ................................................................................................. 3

## Chapter 2. Elemental Tests

2.1. General ........................................................................................................................................ 4  
2.2. Review of Research on Elemental Tests for Shear Bond and End Anchorages ............... 4  
2.3. Shear Bond Elemental Tests ..................................................................................................... 6  
  2.3.1. Specimen Description and Test Set Up ............................................................................ 6  
  2.3.2. Test Procedure .................................................................................................................. 10  
  2.3.3. Test Results ...................................................................................................................... 10  
2.4. End Anchorage Elemental Tests ............................................................................................ 13  
  2.4.1. Specimen Description and Test Set Up ............................................................................ 13  
  2.4.2. Test Procedure .................................................................................................................. 15  
  2.4.3. Test Results ...................................................................................................................... 15  
2.5. Concluding Remarks .................................................................................................................. 17

## Chapter 3. Strength and Stiffness Prediction of Composite Slabs by Simple Mechanical Model

3.1. General ........................................................................................................................................ 18
3.2. Review of Methods of Prediction of Composite Slab Strength by Means of
Semi-Empirical Formulations and Simple Mechanical Models ...................... 19
3.3. SDI-M Method ............................................................................................... 27
3.4. Iterative Method ............................................................................................. 27
3.5. Direct Method .................................................................................................. 34
3.6. Comparison of Calculated and Test Results ................................................. 35
3.7 Concluding Remarks ....................................................................................... 40

Chapter 4. Strength and Stiffness Prediction of Composite Slab by Finite
Element Model
4.1. General ............................................................................................................ 41
4.2. Review of Finite Element Method for Composite Slabs ................................. 42
4.3. Finite Element Model ....................................................................................... 43
  4.3.1. Structure Model .......................................................................................... 43
  4.3.2. Material Model .......................................................................................... 45
4.4. Method of Analysis .......................................................................................... 48
4.5. Results of Analysis and Discussion ................................................................. 49
4.6 Concluding Remarks ....................................................................................... 52

Chapter 5. Long Span Composite Slab Systems
5.1. General ............................................................................................................ 53
5.2. Construction Phase ......................................................................................... 57
5.3. Service Phase ................................................................................................... 60
5.4. Specimen Description and Instrumentation .................................................... 60
5.5. Load Test Procedure ....................................................................................... 64
5.6. Test vs. Analysis Results ................................................................................ 65
5.7. Evaluation of the Floor Vibrations ................................................................. 67
5.8. Proposed Detailed Connection ....................................................................... 69
5.9. Concluding Remarks ..................................................................................... 70
Chapter 6. Reduction Factor, ϕ

6.1. General....................................................................................................................... 71

6.2. Review of Probabilistic Concepts of Load and Resistance Factor Design ............ 71

6.2.1. Reliability Index................................................................................................ 72

6.2.2. AISC LRFD Approach for the Resistance Factor............................................. 74

6.2.3. AISI LRFD Approach for the Resistance Factor ............................................... 75

6.3. Statistical Data......................................................................................................... 76

6.3.1. Material Factor, M ............................................................................................ 77

6.3.2. Fabrication Factor F .......................................................................................... 78

6.3.3. Professional Factor, P ..................................................................................... 79

6.3.4. Load Statistic..................................................................................................... 79

6.4. The Resistance Factor............................................................................................... 80

6.5. Concluding Remarks............................................................................................... 82

Chapter 7. Conclusions and Recommendations.......................................................... 83

References..................................................................................................................... 85

VITA.................................................................................................................................. 96
# LIST OF FIGURES

2-1. Profile shapes ............................................................................................................. 8
2-2. Embossment types ...................................................................................................... 8
2-3. Shear bond test .......................................................................................................... 9
2-4. Shear bond specimen with frames for lateral force .................................................. 9
2-5. Shear stress vs. slip of specimen SB2-2-A ................................................................. 12
2-6. Shear stress vs. slip of specimen SB6-1-B ................................................................. 12
2-7. Details of the end anchorage specimens ..................................................................... 13
2-8. End anchorage test .................................................................................................... 14
2-9. Load vs. deck to concrete slip of specimen EA1-1-B .................................................. 16
2-10. Load vs. deck to concrete slip of specimen EA2-1-A ................................................ 16

3-1. m and k shear bond regression line ............................................................................. 20
3-2. Partial interaction theory (Stark and Brekelmans 1990) ............................................. 22
3-3. Simplified relation between $M_p'$ and $N_b$ (Stark and Brekelmans 1990) .......... 22
3-4. Boundary curve based on the partial interaction theory .......................................... 24
3-5. Free body diagram of the forces action in the composite slab section (Patrick 1990, Patrick and Bridge 1994) ................................................................. 25
3-6. Plot of $M_u$ vs. $T$ (Patrick 1990, Patrick and Bridge 1994) ..................................... 26
3-7. Boundary curve for the ultimate bending moment capacity (Patrick 1990, Patrick and Bridge 1994) ................................................................. 26
3-8. Reinforcing effects of some devices .......................................................................... 27
3-9. Forces acting on the cross section ............................................................................. 28
3-10. Shear bond interaction ............................................................................................ 29
3-11. Concrete bottom fiber elongation, $dL$, and slip diagrams ..................................... 31
3-12. Additional load carrying capacity from the deck ..................................................... 32
3-13. Forces acting on the cross section for the direct method ......................................... 34
3-14. Test setup ................................................................................................................ 37
3-15. Test vs. predicted strength ...................................................................................... 38
3-16. Load vs. mid-span deflection: (a) slab-4, (b) slab-15, (c) slab-21 ......................... 39

4-1. Schematic model of steel deck to concrete slip ........................................................ 44
4-2. Typical finite element model ..................................................................................... 44
4-3. Von Mises yield surface in the principal stress space .............................................. 45
4-4. Concrete failure surface in principal stress space ..................................................... 46
4-5. Concrete uniaxial compressive stress-strain relation ............................................... 47
4-6. Typical shear bond shear stress vs. slip ................................................................. 47
4-7. (a) Shear stud to steel deck interaction, and (b) puddle weld to steel deck interaction ................................................................. 48
4-8. General arc-length method ...................................................................................... 49
4-9. Slab-4: (a) Load vs. mid-span deflection. (b) Load vs. end-slip .............................. 50
4-10. Slab-15: (a) Load vs. mid-span deflection. (b) Load vs. end-slip............................... 50
4-11. Slab-21: (a) Load vs. mid-span deflection. (b) Load vs. end-slip............................... 51
4-12. Composite slab strength: FEM vs. experimental ........................................................ 51

5-1. Prototype 1 and prototype 2 of Ramsden (1987) deck profiles ................................. 54
5-2. Innovative light weight and long-span composite floor (Hillman 1990, Hillman and Murray 1994) .............................................................................................................. 54
5-3. Slimflor system (British Steel, Steel Construction Institute 1997).............................. 55
5-4. 6 in, 4.5 in and 3 in deep profiles.................................................................................. 56
5-5. Yield strength and deflection limit states of the construction (non-composite) phase ......................................................................................................................... 58
5-6. Steel deck weight vs. span length of single span systems........................................... 59
5-7. Steel deck weight vs. span length of double span systems ........................................ 59
5-8. System configuration of LSS1 and LSS2................................................................. 61
5-9. Strain gage and shear stud schedules of LSS1......................................................... 62
5-10. Strain gage and shear stud schedules of LSS2......................................................... 63
5-11. Test set-up .................................................................................................................. 64
5-12. Map of cracks in LSS1.............................................................................................. 65
5-13. Map of cracks in LSS2.............................................................................................. 65
5-14. Load vs. mid-span deflection of LSS1....................................................................... 66
5-15. Load vs. mid-span deflection of LSS2....................................................................... 66
5-16. Normalized relative power vs. frequency of LSS1 ................................................ 68
5-17. Normalized relative power vs. frequency of LSS2 ................................................ 68
5-18. Proposed beam to girder connection to reduce slab-beam height........................... 70
LIST OF TABLES

2-1. Test parameters ........................................................................................................... 7
2-2. Summary of shear bond test results ............................................................................ 11
2-3. Test parameters ........................................................................................................... 14
2-4. Summary of the end anchorage test results................................................................. 15

3-1. Test parameters ........................................................................................................... 36
3-2. Prediction vs. test results............................................................................................. 37

4-1. Finite element vs. test results ........................................................................................ 49

5-1. Ratios of actual load capacities and permissible load based on
allowable deflection to 50 and 150 psf design live loads ........................................... 57
5-2. Section properties of profiles 1, 2 and 3 ..................................................................... 58
5-3. Summary of ultimate load capacity and permissible load based on
allowable deflection ....................................................................................................... 67

6-1. β vs. pf ....................................................................................................................... 73
6-2. Statistical data of f_c', f_y, f_s,max and f_s,min ............................................................... 77
6-3. Statistical data of t...................................................................................................... 78
6-4. Statistical data of P.................................................................................................... 79
6-5. Statistical data of dead and live loads ......................................................................... 79
6-6. Calculated Φ factors for SDI-M method (AISI-LRFD Approach) ......................... 81
6-7. Calculated Φ factors for direct method (AISI-LRFD Approach) ......................... 81
6-8. Calculated Φ factors for SDI-M method (AISC-LRFD Approach) ....................... 81
6-9. Calculated Φ factors for direct method (AISC-LRFD Approach) ....................... 81
LIST OF NOTATIONS

A_{bf} = area of steel deck bottom flange / unit width of slab

A_s = steel deck cross sectional area

A_{webs} = area of steel deck webs / unit width of slab

a = depth of concrete stress block

= \frac{A_s f_y}{0.85 f_c'} b \quad (Eqln.(3-6))

= \frac{F_s + F_{st}}{0.85 f_c'} b \quad (Eqln.(3-24))

b = section width

C = resultant of concrete compressive force

c = depth of the neutral axis of composite section

D_n = nominal value of dead load

d = distance of the steel deck centroid to the top surface of the slab (effective depth)

= length of each segment

dL_i, dL_c = elongation of the bottom fiber of concrete slab of segment i

dL_c = elongation of the segment at the mid-span

d_c = deflection of the partially composite section

d_s = deflection of the steel deck

E_s = elastic modulus of steel deck

E_o, E_{sc} = initial and secant modulus of concrete

e_1, e_2, e_3 = moment arms of T_1, T_2, T_3 (Eqln.(3-9))

F = minimum anchorage force (Chapter 3) = f_y \left( A_s - \frac{A_{webs}}{2} - A_{bf} \right), (Eqln.(3-8))

= fabrication factor (Chapter 6)

F_m = mean of fabrication factor
$F_s, F_{st} = \text{tensile force in the steel deck resulted from the effect of shear bond and end anchorages respectively}$

$F_{s,\text{limit}} = \text{upper limit of } F_s$

$f_{\text{anchorage}} = \text{stress in the steel deck induced by end anchorages}$

$f_{\text{bond}} = \text{stress in the steel deck induced by shear bond force, } f_b$

$f_c' = \text{concrete compressive strength}$

$f_{c',\text{m}} = \text{mean of concrete compressive strength} = \mu f_c'$

$f_{\text{cast}} = \text{stress in the steel deck induced by concrete casting}$

$f_s = \text{shear bond force per unit length}$

$f_{\text{shore}} = \text{stress in the steel deck induced by shore removal}$

$f_{s,\text{max}}, f_{s,\text{min}} = \text{maximum and minimum of } f_s$

$f_t = \text{concrete tensile strength}$

$f_w = \text{stress in the steel deck induced by puddle welds}$

$f_y = \text{steel deck yield stress}$

$f_{\text{yc}} = \text{corrected steel deck yield stress due to concrete casting and shoring}$

$f_y^* = \text{remaining strength of the steel deck}$

$f_{y,\text{m}} = \text{mean of steel deck yield stress} = \mu f_y$

$f_1, f_2 = \text{elastic concrete compressive and tensile stress at the extreme fiber}$

$h_b = \text{concrete depth above steel deck rib}$

$h_1 = \text{depth of the concrete flange (concrete above steel deck rib)}$

$I_{\text{eff}} = \text{effective cross sectional inertia of the slab}$

$I_i = \text{effective cross sectional inertia of a segment}$

$i = \text{sequence number of a segment}$

$L = \text{span length of the slab}$

$L' = \text{shear span length}$

$L_{\text{c}} = \text{cantilever length}$


\( L_n \) = nominal value of live load  
\( L_s \) = shear bond length  
\( M \) = bending moment, general (Chapter 3)  
\( = \) material factor (Chapter 6)  
\( M_{et} \) = first yield bending moment  
\( M_m \) = mean of material factor  
\( M_{m,SDI}, M_{m,Direct} \) = means of material factor with regard to the SDI and Direct method, respectively  
\( M_{nc}, M_{nd} \) = nominal moment capacity: phase-1 and phase-2, respectively  
\( M_p \) = steel deck plastic moment capacity  
\( M_{nu}, M_n \) = nominal bending moment  
\( m \) = bending moment caused by a unit load  
\( N_b \) = \( k \ell_c' h_b' \) (Eqn.(3-3))  
\( N_r \) = number of shear studs / unit width of slab  
\( n \) = number of segment from the support to the mid-span  
\( P \) = professional factor  
\( P_m \) = mean of professional factor  
\( P_f \) = probability of failure  
\( Q_{i}, Q_m \) = load effect, mean of load effect  
\( Q_n \) = nominal strength of single shear stud  
\( q, q_c, q_d \) = load carrying capacity: total, phase-1, phase-2, respectively  
\( R \) = reduction factor due to insufficient number of shear studs  
\[ \text{to provide anchorage} = \frac{N_r Q_n}{F} \]  
\( R_n, R_m \) = nominal resistance, mean of resistance  
\( S \) = steel deck section modulus  
\( s_i \) = total slip at a section  
\( T \) = resultant of tensile force in steel deck
$T_1, T_2, T_3$ = forces acting in top flange, web and bottom flange of steel deck

$t = \text{steel deck thickness}$

$t_m = \text{mean of steel deck thickness} = \mu_t$

$u_i^d = \text{nodal displacement of steel deck beam element in d.o.f.-1 direction (horizontal)}$

$u_i^c = \text{nodal displacement of concrete beam element in d.o.f.-1 direction (horizontal)}$

$V, V_R, V_Q$

= coefficients of variation: general, resistance, load effect

$V_M, V_F, V_P, V_{f'_c}, V_{f'_y}, V_t$

= coefficients of variation of: material, fabrication, professional factors, concrete compressive strength, steel deck yield stress, steel deck thickness

$V_{M,SDI}, V_{M,Direct}$

= coefficients of variation of material factor with regard to the SDI and Direct method, respectively

$V_u = \text{ultimate shear capacity}$

$x, x_i = \text{distance from the support to the section being investigated}$

$y_c = \text{horizontal projection of } y_d$

$y_d = \text{depth of deck c.g. from concrete c.g.}$

$y_s = \text{horizontal slip of steel deck relative to the concrete}$

$y_1, y_2 = \text{moment arm of } F_s \text{ and } F_{st}, \text{ respectively}$

$\beta = \text{reliability index}$

$\varepsilon, \varepsilon_{cu} = \text{concrete strain, concrete strain at the peak compressive stress}$

$\varepsilon_s = \text{steel deck strain}$

$\Phi = \text{standard normal probability function}$

$\phi = \text{design resistance factor}$

$\gamma_D, \gamma_L = \text{dead and live load factors}$

$\gamma_i = \text{design load factor}$

$\gamma_D = \text{correction due to diagonal shear cracking}$

$\kappa = \text{fraction of the support reaction, R in Eqn.(3-11)}$
λ, λ_R, λ_Q = log-normal mean: general, resistance, load effect

μ = coefficient of friction between the deck and concrete

μ_{f'_c} = mean of concrete compressive strength = f'_{c,m}

μ_{f_y} = mean of steel deck yield stress = f_{y,m}

μ_t = mean of steel deck thickness = t_m

θ = rotation of cross sectional plane (Chapter 4)

= central safety factor (Chapter 6)

ρ = reinforcement ratio = A_s / b_d

σ, σ_p, σ_t = standard deviations: general, professional factor, steel deck thickness

τ_{shear bond} = shear bond strength

Ψ = \left[ \frac{\gamma_D}{L_n} \right] / \left[ 1.05 \frac{D_n}{L_n} + 1 \right], \quad (Eqn.(6-18))

ζ, ζ_R, ζ_Q = log-normal standard of deviation: general, resistance, load effect

Ω_i = \frac{\int M m ds}{L} \quad (Eqn.(3-22))