



Construction Industry Institute®

## Construction Productivity Research Program Phase III

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## Construction Industry Institute

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CONSTRUCTION PRODUCTIVITY RESEARCH PROGRAM  
PHASE III

by

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A Report to  
Construction Industry Institute  
The University of Texas at Austin

Under the Guidance of  
CII Research Team 252  
Craft Productivity Research Program

CII Research Report 252-11  
January 2012

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## EXECUTIVE SUMMARY

Achieving a 50% improvement in construction craft productivity in six years would break a century old tradition of stagnation, a trend that has been interrupted only by periodic incremental improvement. The first and the second phases of a six-year research program were successfully completed in the last two years. The following report details the findings from the third phase in this past year.

Direct work typically amounts to no more than 35-45% of a craftsman's time on the job. To improve craft productivity, direct work time must be improved. To increase direct work time, the availability of materials, information and tools at the workplace must be improved. There will be no "magic bullet" that will make this happen, but rather a series of innovations that together produce change. They will include a combination of broad improvements in practice and focused improvements in technology and process.

To achieve these improvements, Research Team (RT) 252's rolling, five-phase program injects innovations annually via a sequence of innovation workshops, field trials, analysis, and implementation tool delivery. Each phase of the program involves the following: 1) analyses of the CII BM&M data to identify best practices that appear to have an impact on productivity, 2) exploring opportunities for productivity improvement through craft information, technology support for labor, work packaging/organization, and human behavior, and 3) soliciting innovation input from structured workshops and team members' expertise.

Analysis of the CII Benchmarking and Metrics (BM&M) data in this phase of the program found relationships between certain management practices and productivity in the concrete trades. The results indicate that projects with a high level of implementation of safety programs, information systems integration, materials management systems, team-building, front end planning, constructability, and change management experienced better labor productivity in the concrete trades. These findings suggest an overall level of synergy with the practices that were found to be related to better productivity in the concrete trades. These findings also suggest an overall level of synergy with the practices that were found to be related to better productivity in the mechanical and electrical trades, as reported in previous phases.

Thus, RT 252's efforts in the first research phase also focused on a thorough search and definition of best productivity practices. When these practices have become rigorously weighted and properly structured, they will become part of a Best Productivity Practices Implementation Index (BPPII). The BPPII is in the process of being validated in the last phase and this phase, and will be delivered as an implementation tool in the final phase of the program. No existing CII tool addresses productivity as directly as the BPPII will. Until it is fully developed, however, exciting innovations will continue to emerge and this research program will continue to track and analyze them.

For this phase of the program, the team has charted new directions for the industry by producing implementation resources that can increase craft wrench time, reduce rework, and reduce the number of hours required to complete one unit of work. The investigations are as following: 1) using innovations to reduce the number of work hours required to complete one unit of work; 2) reducing the amount of rework on

projects; 3) using the BPPII as a comprehensive productivity improvement roadmap. There are other documents and products related to Phase II that should be considered companion documents to this one. The first, *A Guide to Construction Rework Reduction*, (CII IR 252-2b) is a useful tool for implementation. This final report to Phase III provides the research background for that guide, but the guide includes additional content that the reader may wish to access by getting a copy. The research summary for Phase III, *Construction Productivity Research Program Phase III*, (CII RS 252-1b) is also a useful document related to this one.

Implementing the best productivity practices identified in this first phase and the second phase is expected to result in significant productivity improvement on your project. More is yet to come in subsequent project phases. This report includes five chapters. Chapter 1 provides an overview of the Construction Productivity Program. Chapter 2 analyzes project practices related to concrete productivity. Chapter 3 take an in-depth look at the concrete innovations. Chapter 4 discusses the Rework Reduction Program (RRP) research. Chapter 5 updates the best productivity practices implementation index (BPPII). Chapter 6 is the conclusion of this report.

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# TABLE OF CONTENTS

|                                                                          |           |
|--------------------------------------------------------------------------|-----------|
| <b>CHAPTER 1 . INTRODUCTION.....</b>                                     | <b>1</b>  |
| 1.1 Background .....                                                     | 1         |
| 1.2 Definition of Construction Productivity.....                         | 2         |
| 1.3 Primary Objective .....                                              | 3         |
| 1.4 Specific Objectives of the Research.....                             | 4         |
| 1.5 The Shift from Craft Productivity to Construction Productivity ..... | 6         |
| <b>CHAPTER 2 . ANALYSES OF PROJECT PRACTICES AND PRODUCTIVITY.....</b>   | <b>8</b>  |
| 2.1 Front End Planning.....                                              | 9         |
| 2.2 Team Building.....                                                   | 10        |
| 2.3 Change Management.....                                               | 12        |
| 2.4 Materials Management .....                                           | 14        |
| 2.5 Safety.....                                                          | 16        |
| 2.6 Integration of Information Systems.....                              | 19        |
| 2.7 Constructability .....                                               | 20        |
| 2.8 Summary .....                                                        | 21        |
| <b>CHAPTER 3 . CONCRETE CONSTRUCTION PRODUCTIVITY INNOVATIONS .....</b>  | <b>23</b> |
| 3.1 Grade 100 Steel Reinforcement .....                                  | 23        |
| 3.1.1 Background.....                                                    | 23        |
| 3.1.2 Scope.....                                                         | 26        |
| 3.1.3 Calculations .....                                                 | 28        |
| 3.1.4 Varying Analyses .....                                             | 37        |
| 3.1.5 Labor and Material Costs .....                                     | 45        |
| 3.1.6 Effects on Productivity .....                                      | 54        |
| 3.1.7 Monitoring the Effects.....                                        | 56        |
| 3.1.8 Conclusion.....                                                    | 58        |
| 3.2 Self -consolidating Concrete .....                                   | 60        |
| 3.2.1 Background on Self-consolidating Concrete .....                    | 60        |
| 3.2.2 Use of Self-consolidating Concrete.....                            | 61        |
| 3.2.3 Unit Rates .....                                                   | 61        |
| 3.2.4 Analysis .....                                                     | 66        |
| 3.2.5 Conclusion.....                                                    | 68        |

|                                                                                                    |            |
|----------------------------------------------------------------------------------------------------|------------|
| 3.3 Modular Formwork Systems .....                                                                 | 69         |
| 3.3.1 Background.....                                                                              | 69         |
| 3.3.2 Analysis .....                                                                               | 72         |
| 3.3.3 Conclusion.....                                                                              | 79         |
| 3.4 Chapter Conclusions .....                                                                      | 80         |
| <b>CHAPTER 4 REWORK REDUCTION PROGRAM .....</b>                                                    | <b>81</b>  |
| 4.1 Introduction .....                                                                             | 81         |
| 4.1.1 Background and Need .....                                                                    | 81         |
| 4.1.2 Scope and Objectives .....                                                                   | 81         |
| 4.1.3 Methodologies .....                                                                          | 82         |
| 4.1.4 Definition of rework .....                                                                   | 83         |
| 4.1.5 Impact of rework on project performance .....                                                | 83         |
| 4.1.6 Classification of the causes of rework.....                                                  | 84         |
| 4.1.7 Rework reduction tools.....                                                                  | 87         |
| 4.1.8 Literature review summary.....                                                               | 89         |
| 4.1.9 Nuclear Power Plant Maintenance and Modification.....                                        | 91         |
| 4.1.10 The Company's Reporting System.....                                                         | 92         |
| 4.2 Conceptual Model for Rework Reduction Program.....                                             | 94         |
| 4.2.1 Introduction .....                                                                           | 94         |
| 4.2.2 Overview of Rework Reduction Program Model.....                                              | 94         |
| 4.2.3 Description of the Rework Reduction Program Model Process.....                               | 97         |
| 4.3 Case Study and Analysis .....                                                                  | 111        |
| 4.3.1 Introduction .....                                                                           | 111        |
| 4.3.2 Investigation of the Company's Rework Program .....                                          | 111        |
| 4.3.3 Nuclear Power Plant Maintenance and Modification.....                                        | 120        |
| 4.3.4 Data Collection and Fusion .....                                                             | 126        |
| 4.3.5 Rework Impact Evaluation .....                                                               | 137        |
| 4.4 Conclusions and Recommendations.....                                                           | 149        |
| 4.4.1 Introduction .....                                                                           | 149        |
| 4.4.2 Findings and Conclusions.....                                                                | 149        |
| 4.4.3 Recommendations for Future Studies.....                                                      | 155        |
| <b>CHAPTER 5 AN UPDATE OF THE BEST PRODUCTIVITY PRACTICES<br/>IMPLEMENTATIONINDEX (BPPII).....</b> | <b>157</b> |
| 5.1 Introduction .....                                                                             | 157        |

|                                                              |            |
|--------------------------------------------------------------|------------|
| 5.2 Project Descriptions .....                               | 157        |
| 5.3 BPPII Categories .....                                   | 162        |
| 5.3.1. Category I - Materials Management.....                | 162        |
| 5.3.2. Category II - Equipment Logistics .....               | 163        |
| 5.3.3. Category III - Craft Information Systems.....         | 163        |
| 5.3.4. Category IV - Human Resource Management.....          | 164        |
| 5.3.5. Category V – Construction Methods .....               | 164        |
| 5.3.6. Category VI – Environmental Safety and Health .....   | 165        |
| 5.4 Implementation Levels of Projects.....                   | 166        |
| 5.4.1 Materials Management Category.....                     | 166        |
| 5.4.2 Equipment Logistic Category .....                      | 169        |
| 5.4.3 Craft Information Category .....                       | 171        |
| 5.4.4 Human Resource Management Category .....               | 175        |
| 5.4.5 Construction Method Category .....                     | 177        |
| 5.4.6 Environmental, Safety, and Health Category .....       | 180        |
| 5.5 Conclusions .....                                        | 183        |
| <b>CHAPTER 6 . CONCLUSIONS .....</b>                         | <b>184</b> |
| <b>REFERENCES .....</b>                                      | <b>187</b> |
| <b>APPENDIX A – SELF-CONSOLIDATING CONCRETE SURVEY .....</b> | <b>192</b> |
| <b>APPENDIX B – ASTM JPM SPREADSHEET.....</b>                | <b>196</b> |
| <b>APPENDIX C – BPPII ELEMENTS DESCRIPTIONS.....</b>         | <b>197</b> |



## LIST OF TABLES

|                                                                                                                                                                    |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 2-1. Front End Planning versus Concrete Craft Productivity .....                                                                                             | 10 |
| Table 2-2. Team Building versus Concrete Craft Productivity .....                                                                                                  | 11 |
| Table 2-3. Change Management versus Concrete Craft Productivity .....                                                                                              | 12 |
| Table 2-4. Material Management versus Concrete Craft Productivity .....                                                                                            | 15 |
| Table 2-5. Safety versus Concrete Craft Productivity .....                                                                                                         | 17 |
| Table 2-6. Integration of Information Systems versus Concrete Craft Productivity .....                                                                             | 19 |
| Table 2-7. Constructability versus Concrete Craft Productivity .....                                                                                               | 20 |
| Table 2-8. List of Significant Practices for Each Management Program .....                                                                                         | 22 |
| Table 3-1. Moment Strengths Based on Varying Concrete Strengths.....                                                                                               | 38 |
| Table 3-2. Reduction of Minimum Required Area of Reinforcing Steel .....                                                                                           | 40 |
| Table 3-3. Effect of Beam length on Area of Reinforcement for Grade 60 and Grade 100 Steel.                                                                        | 43 |
| Table 3-4. Percent Reductions in Reinforcing Steel (Grade 100 vs. Grade 60) for Varying Cross-<br>Sectional Areas.....                                             | 44 |
| Table 3-5. Percent Reductions in the Cost of Materials (Grade 100 vs. Grade 60) for Varying<br>Concrete Strength Designs .....                                     | 48 |
| Table 3-6. Percent Reductions in the Cost of Installation (Grade 100 vs. Grade 60 Steel<br>Reinforcement) for Varying Concrete Strength Designs .....              | 50 |
| Table 3-7. Percent Reductions in the Cost of Installation and Materials (Grade 100 vs. Grade 60<br>Steel Reinforcement) for Varying Concrete Strength Designs..... | 51 |
| Table 3-8. Effects of Varying Relative Cost of Grade of Steel on the Cost of Materials per Foot<br>for Given Beam Designs .....                                    | 52 |
| Table 3-9. Effects of Varying Relative Cost of Grade of Steel on the Total Cost for Given Beam<br>Designs .....                                                    | 54 |

|                                                                                                                     |     |
|---------------------------------------------------------------------------------------------------------------------|-----|
| Table 3-10. SCC advantages and disadvantages .....                                                                  | 64  |
| Table 3-11. Comparing modular, prefab, and stick-built formwork systems.....                                        | 71  |
| Table 3-12. The Pros and Cons of using the modular formwork .....                                                   | 73  |
| Table 3-13. The Pros and Cons of using the stick-build formwork.....                                                | 74  |
| Table 3-14. A “Typical” Cost Breakdown of Each Slab Formwork System for a Single Set-up or<br>Tear-down Cycle ..... | 75  |
| Table 3-15. Modular Formwork System Compared to Stick-built by Backer Concrete .....                                | 76  |
| Table 4-1. Deviation Categories of the Causes of Rework .....                                                       | 85  |
| Table 4-2. Rework Reduction Program in the Management Hierarchy .....                                               | 94  |
| Table 4-3. List of Identified Root Causes of Rework.....                                                            | 101 |
| Table 4-4. Rework Evaluation Structure .....                                                                        | 107 |
| Table 4-5. The Company's Rework Causes Category .....                                                               | 113 |
| Table 4-6. Total Number of Rework Events for Year 2006-2008.....                                                    | 131 |
| Table 4-7. Number of Rework Event Records Retrieved.....                                                            | 135 |
| Table 4-8. Number of Rework Event Records Reviewed for Investigation.....                                           | 135 |
| Table 4-9. Numbers of Full Reports involved in Rework Impact Evaluation.....                                        | 136 |
| Table 4-10. The Company 's Nuclear Segment OM&A Expenses.....                                                       | 138 |
| Table 4-11. Rework Hours and Direct Cost as a Percentage of Total Work Size .....                                   | 141 |
| Table 5-1. Industry Groups of Projects .....                                                                        | 158 |
| Table 5-2. Contract Types of Projects.....                                                                          | 158 |
| Table 5-3. Natures of Projects .....                                                                                | 159 |
| Table 5-4. Types of Projects.....                                                                                   | 159 |
| Table 5-5. Levels of Project Complexities .....                                                                     | 160 |
| Table 5-6. Complexity of Projects.....                                                                              | 160 |
| Table 5-7. Types of Projects.....                                                                                   | 161 |
| Table 5-8. Overall Implementation Level of Materials Management Category .....                                      | 168 |

|                                                                                            |     |
|--------------------------------------------------------------------------------------------|-----|
| Table 5-9. Overall Implementation Level of Equipment Logistics Category .....              | 170 |
| Table 5-10. Overall Implementation Level of Craft Information Systems Category .....       | 173 |
| Table 5-11. Overall Implementation Level of Human Resource Management Category .....       | 176 |
| Table 5-12. Overall Implementation Level of Construction Methods Category .....            | 180 |
| Table 5-13. Overall Implementation Level of Environmental Safety and Health Category ..... | 182 |

# LIST OF FIGURES

|                                                                                                                                     |    |
|-------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1-1: The Construction Productivity Research Program's strategy for productivity improvement.....                             | 4  |
| Figure 1-2. Construction Productivity Program timeline .....                                                                        | 5  |
| Figure 2-1. BM&M's Average Scores of Critical Practices involved in Front End Planning .....                                        | 10 |
| Figure 2-2. BM&M's Percentage of Sampled Projects include Major Suppliers in Team Building Process.....                             | 11 |
| Figure 2-3. BM&M's Average Scores of Critical Practices involved in Change Management....                                           | 13 |
| Figure 2-4. BM&M's Average Score on Critical Materials management Practices.....                                                    | 16 |
| Figure 2-5. BM&M's Average Scores of Critical Safety Practices .....                                                                | 18 |
| Figure 2-6. The BM&M's Average Level of Integration Use across Work Functions.....                                                  | 20 |
| Figure 2-7. BM&M's Average Performance on Tracking Lessons learned from Previous Constructability Program.....                      | 21 |
| Figure 3-1. Stress-Strain Curves for Various Grades of Steel (American Concrete Institute, 2010) .....                              | 24 |
| Figure 3-2. Example Beam Design (American Concrete Institute, 2010).....                                                            | 27 |
| Figure 3-3. Relationship between strength reduction factor and strain for Grade 100 steel (American Concrete Institute, 2010) ..... | 30 |
| Figure 3-4. Cross Section and Compression/Tension Zones with Variables Labeled (Portland Cement Association, 2002) .....            | 34 |
| Figure 3-5. Relationship between Concrete Strength and Area of Reinforcing Steel Required .....                                     | 39 |
| Figure 3-6. Maximum Compression Zone Depths for Beams Designed Using Grade 60 and Grade 100 Steel .....                             | 41 |
| Figure 3-7. Relationship between Beam Length and Area of Reinforcing Steel Required.....                                            | 42 |

|                                                                                                                                            |     |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 3-8. Effect of Concrete Strength on the Cost of Steel per Beam Design .....                                                         | 47  |
| Figure 3-9. Effect of Concrete Strength on the Cost of Installation of Reinforcement per Beam<br>Design.....                               | 49  |
| Figure 3-10. Effect of Concrete Strength on the Cost of Installation and Materials of<br>Reinforcement per Beam Design.....                | 51  |
| Figure 3-11. Effect of Concrete Strength on Total Cost of Beam for Grade 100 vs. Grade 60 Steel<br>Cost Ratio of 1.5.....                  | 53  |
| Figure 3-12. SCC slump test measurement ( <a href="http://www.selfconsolidatingconcrete.org">www.selfconsolidatingconcrete.org</a> ) ..... |     |
| Figure 3-13. J-ring test ( <a href="http://www.concretenetwork.com">www.concretenetwork.com</a> ).....                                     |     |
| Figure 3-14. Labor Unit Rates for Concrete Placement at various projects .....                                                             | 63  |
| Figure 3-15. ASTM Job Productivity Measurement (JPM) Productivity Differentials .....                                                      | 67  |
| Figure 3-16. Project (\$/sf) of the slab formwork system within ENR Labor Rate Report in 2010                                              | 78  |
| Figure 4-1. Generic Cause-and-Effect Rework Diagram Derived From Qualitative Data .....                                                    | 86  |
| Figure 4-2. COAA's Fishbone Rework Cause Classification.....                                                                               | 87  |
| Figure 4-3. Process Flow Chart of RRP .....                                                                                                | 96  |
| Figure 4-4. Rework Tracking and Cause Classification.....                                                                                  | 97  |
| Figure 4-5. Rework Tracking Process.....                                                                                                   | 100 |
| Figure 4-6. Rework Impact Evaluation and Trend Analysis .....                                                                              | 104 |
| Figure 4-7. Corrective Action Planning .....                                                                                               | 108 |
| Figure 4-8. Process Flow Chart of The Company's Nuclear Rework Program .....                                                               | 115 |
| Figure 4-9. Aerial Photograph of the Nuclear Power Station.....                                                                            | 121 |
| Figure 4-10. Evidence Chain for the Rework Case Study Analysis.....                                                                        | 128 |
| Figure 4-11. Overall Occurrence of Rework by Year .....                                                                                    | 138 |
| Figure 4-12. Overall Occurrence of Rework by Month .....                                                                                   | 139 |
| Figure 4-13. Trend in Rework Labor Hours.....                                                                                              | 140 |
| Figure 4-14. Trend in Direct Cost of the Rework.....                                                                                       | 141 |

|                                                                                   |     |
|-----------------------------------------------------------------------------------|-----|
| Figure 4-15. Percentage Contribution of Root Causes of Rework .....               | 144 |
| Figure 4-16. Rework Occurrence by Root Causes Over the Year.....                  | 145 |
| Figure 4-17. Rework Labor Hours by Root Causes Over Time .....                    | 146 |
| Figure 4-18. Direct Cost of Rework by Root Causes Over Time.....                  | 147 |
| Figure 4-19. Rework Labor Hours by Root Cause Group Over the Time .....           | 148 |
| Figure 4-20. Direct Cost of Rework by Root Cause Group Over the Time .....        | 148 |
| Figure 5-1. Answer Distribution of Materials Management Category.....             | 167 |
| Figure 5-2. Answer Distribution of Equipment Logistics Category.....              | 170 |
| Figure 5-3. Answer Distribution of Craft Information Systems Category .....       | 172 |
| Figure 5-4. Answer Distribution of Human Resource Management Category .....       | 175 |
| Figure 5-5. Answer Distribution of Construction Methods Category .....            | 179 |
| Figure 5-6. Answer Distribution of Environmental Safety and Health Category ..... | 181 |

# CHAPTER 1 . INTRODUCTION

## 1.1 Background

The complexity and longstanding difficulty of promoting significant improvements in construction productivity prompted CII to take an unusual approach to meeting this industry challenge. In 2007, CII formed the Research Team (RT) 252, Construction Productivity Research Program. The program was established with the primary objective of identifying and validating one or more initiatives, techniques, or methods that, if implemented, would result in a breakthrough improvement in construction productivity. This research summary presents the results of the third phase of the RT 252 journey to improve construction productivity.

From its inception, the members of the team grasped the fact that there is no single approach to improving productivity. Instead, they found that a multitude of techniques and methods for improving productivity are used throughout industry, usually in isolation. To counter such fragmented implementation, they decided on an approach that would identify these techniques and synthesize them into a cohesive roadmap. Their intent is to offer a coherent overview of productivity improvement tools to help develop sustained improvements in construction productivity—at least among the companies that use it. While this research summary focuses on the accomplishments of RT 252 during Phase III, it must first revisit the background of the program for the benefit of the reader.

## 1.2 Definition of Construction Productivity

Because construction productivity has been defined in a variety of ways, it is difficult to establish a standard productivity measurement for the industry. The difficulty of measuring productivity has generated a number of questions; these include “What is the best way to measure construction productivity?” and “Has construction productivity been improving or declining over the past several decades?” among others.

Governmental agencies typically define productivity as the ratio of outputs to inputs, either in the form of labor productivity (i.e., industry real output per work hour) or multi-factor productivity (i.e., industry real output per total cost of inputs, including labor, equipment, and materials). In order to control jobsite productivity, a site construction manager is likely to measure productivity differently—either as a performance ratio (e.g., actual quantities installed per estimated quantities installed), direct work rate (i.e., tool or wrench time), or as labor productivity (e.g., work hours per quantities installed). The CII Benchmarking and Metrics (BM&M) committee measures construction productivity as the number of work hours per unit of installed work.

What complicates any discussion of construction productivity is that any of the above-mentioned approaches to productivity measurement are correct and effective at controlling productivity, if used correctly. At the outset of this program, RT 252 adopted the CII BM&M definition of construction productivity, i.e., work hour per unit of installed work. One nuance of this definition is that a lower measurement is better. That is, it is in a project’s best interest to use as few work hours as possible to install a given quantity of work.

### 1.3 Primary Objective

The primary objective of this research program is to significantly improve construction productivity. By combining different approaches, the team works to identify the following opportunities to improve craft performance:

- increasing the time spent on direct work through activity analysis
- implementing innovations with potential to reduce the number of work hours required to complete one unit of work
- reducing the amount of rework
- using the Best Productivity Practice Implementation Index (BPPII) as the basis of a comprehensive productivity improvement roadmap.

The diagram in Figure 1-1 illustrates the synergistic relationships among all of these efforts.

The BPPII is designed to provide initial and ongoing evaluation of a project's planning and implementation levels of the best practices that influence craft productivity. The BPPII roadmap incorporates the following six broad improvement areas: 1) Materials Management, 2) Equipment Logistics, 3) Craft Information Systems, 4) Human Resource Management, 5) Construction Methods, and 6) Environmental, Health, and Safety.

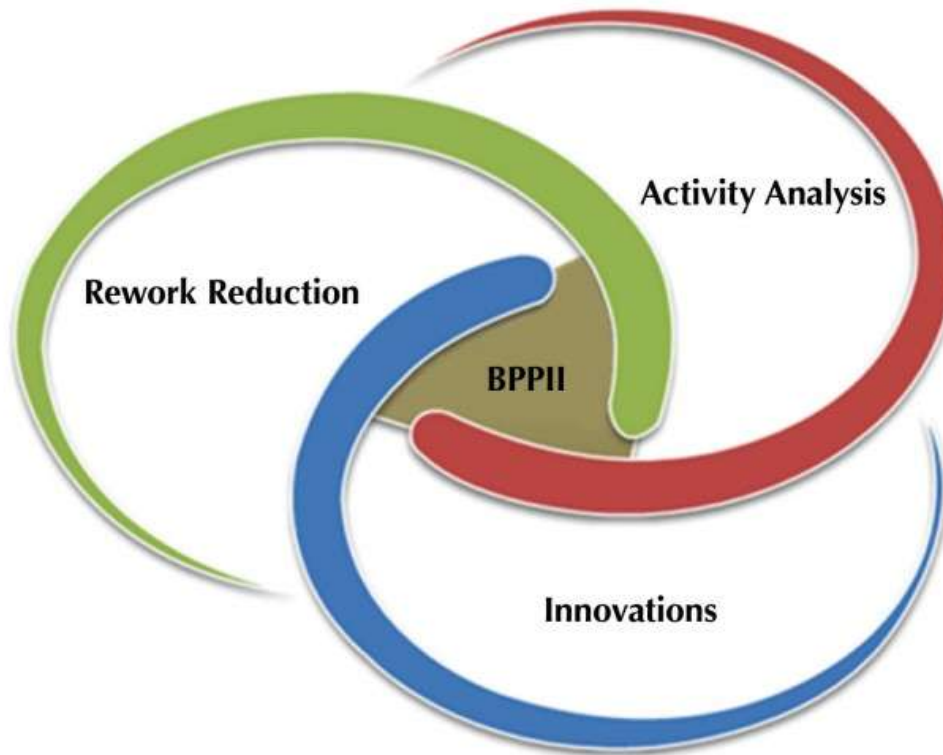


**Figure 1-1. The Construction Productivity Research Program's strategy for productivity improvement**

## **1.4 Specific Objectives of the Research**

The RT 252 vision for promoting significant productivity improvement focuses on the development of the series of deliverables that is outlined in detail in Figure 1-2.

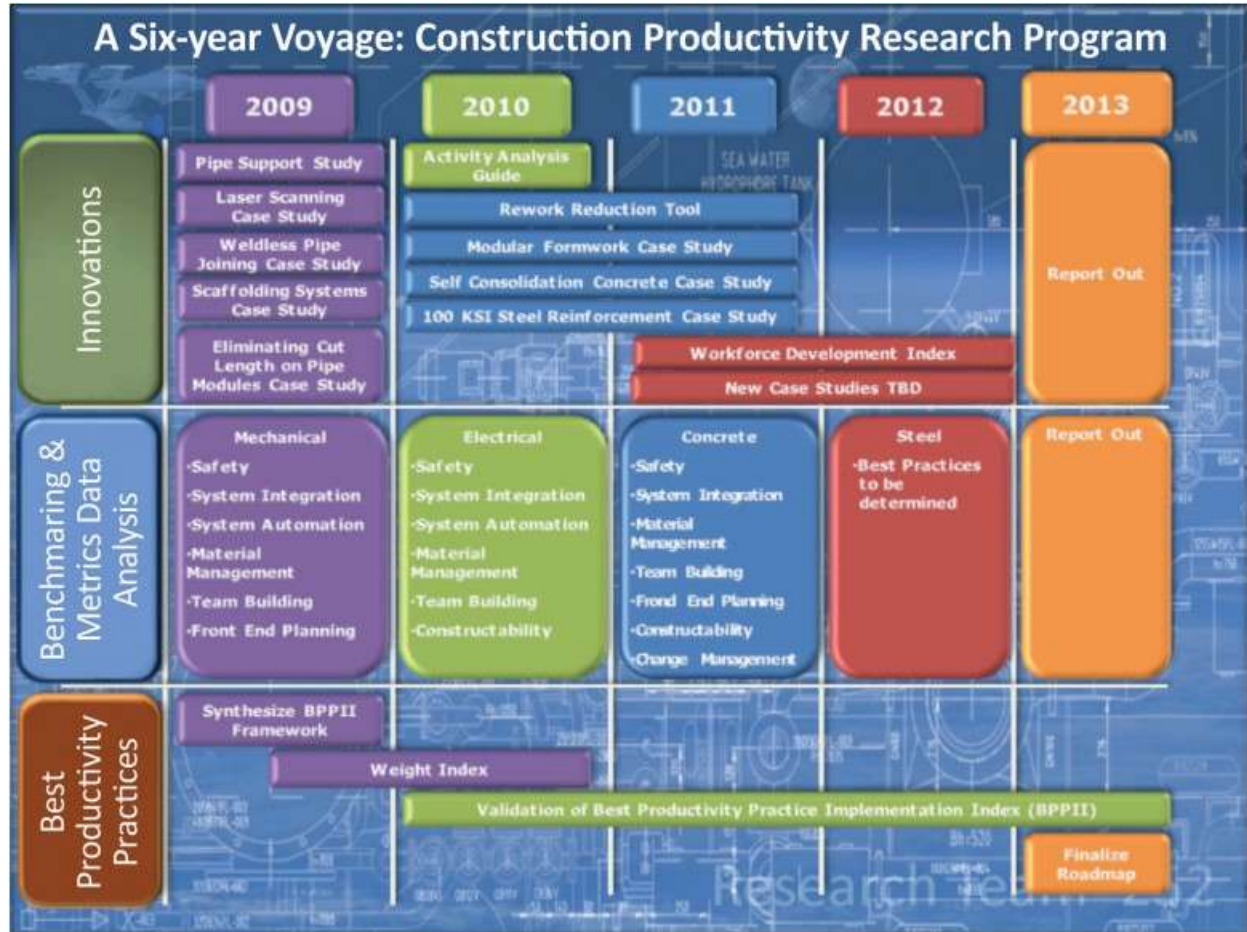


**Figure 1-2. Construction Productivity Program timeline**

Each phase of the RT 252 program examines a series of innovations, both in the form of process innovations and new discrete practices summarized through case studies. In Phase I, the team focused on innovations that were unique to the mechanical trades. (See IR 252-2, *Innovations in Mechanical Construction Productivity*.) While the team received positive feedback from a number of CII member companies that used these case studies for their own internal reviews, other member companies identified other innovations with a larger, cross-cutting scope. In response, the team chose to conduct field studies during Phase II, utilizing an

advanced form of activity analysis, called work sampling. Although work sampling has a long history, the team's investigations indicated that companies implementing more rigorous and continuous processes experience dramatically higher direct work rates. Since improving direct work is one of the program's lines of inquiry into improving craft performance, the team chose to develop an activity analysis guide. (See IR 252-2a, *Guide to Activity Analysis*.) Anticipating potential feedback, calling for more trade-specific innovations, the team focused its Phase III efforts on a combination of cross-cutting innovations (e.g., a rework reduction tool) and on concrete-specific innovations, since the concrete trade is the focus of this phase of the study.

The team's analyses of benchmarking and metrics data continue to identify significant management practices related to better labor productivity on CII projects. The Phase III efforts focused on identifying significant management practices related to the concrete trade. The results of these analyses are presented in the Best Productivity Practice Implementation Index (BPPII), the team's framework for overall productivity improvement. In Phase I, the team's work on the BPPII involved developing its structure and defining the elements necessary to support craft productivity. In Phase II, the focus was on developing a scoring mechanism and beginning a validation process for the index. In Phase III, the team collected additional validation data. (More details are provided below.)

## **1.5 The Shift from Craft Productivity to Construction Productivity**

The original RT 252 charter focused exclusively on improving craft workers' direct work rates. However, as described above, the program's strategy has evolved since its beginnings, and now involves going beyond its initial investigation into improving direct work rates. The program is now investigating the following:

- using innovations to reduce the number of work hours required to complete one unit of work
- reducing the amount of rework on projects
- using the BPPII as a comprehensive productivity improvement roadmap.

Thus, the new name was adopted to better reflect the program's now broader scope.

## CHAPTER 2 . ANALYSES OF PROJECT PRACTICES AND PRODUCTIVITY

Phase III of the Craft Productivity Program focused on ways to improve productivity in concrete construction. Analyses described herein describe the relationship between the implementation level of project practices and their corresponding productivity performance in the concrete trades through a series of statistical analyses utilizing the CII Benchmarking and Metrics dataset.

A project-level analysis was performed using project practice data and corresponding project productivity performance data. The CII BM&M program collects data on specific practices as part of developing an overall index for certain area practices, such as materials management and front end planning. RT 252 identified the specific practices that were statistically correlated to better productivity before including them in the overall practice index. CII defines productivity as the ratio of actual work hours per installed quantity, which is expressed in the Equation 2-1.

$$\text{Equation 2-1: Labor Productivity} = \frac{\text{Actual Workhours}}{\text{Quantity Installed}}$$

Therefore, a better productivity is indicated by a smaller number. Furthermore, to ensure organization confidentiality, the raw productivity metrics were normalized between one and 10 using the Max-Min method of normalization. The practice indexes included in this report only include the specific practices that were found to be significantly related to improved productivity in the concrete trades. The relationship between normalized productivity for the concrete trades with the practice indexes was then compared. For the purpose of the analysis, projects scoring

five percent above the overall median of each practice index were classified as having a high level of use in reference to the overall practice, and projects scoring five percent below the median were defined as having a low level of use.

This chapter presents RT 252's statistical analysis results on concrete trades, examining the relationship between concrete craft productivity and management practices in various areas. In addition, this chapter also presents the identified key practices related to each management area.

## **2.1 Front End Planning**

Front end planning involves the process of developing sufficient strategic information in order to allow owners to address a project's risk and decide to commit resources to maximize the chance for a successful project. RT 252 found the following front end planning practices to be most significant and included them in an overall front end planning composite index:

- 1) integration of constructability feedback into front end planning;
- 2) designation of contingency funds; and
- 3) meeting front end planning objectives in a timely fashion, and in accordance with project schedule requirements.

RT 252 identified a significant relationship between front end planning and concrete craft productivity. By comparison of normalized concrete labor productivity, it is noted that projects with a high level of front end planning are able to improve productivity up to approximately 41.5% compared to the low-level projects (see Table 2-1).

**Table 2-1.Front End Planning versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                              |          |      |      |
|----------|------------------------------------------|------------------------------|----------|------|------|
|          | High Level Front End Planning            | Low Level Front End Planning | $\Delta$ | t    | Sig. |
| Concrete | 3.9                                      | 6.3                          | -2.4     | -2.4 | .02  |
|          | Percent Difference in Labor Productivity |                              |          |      |      |
|          | Front end Planning                       |                              |          |      |      |
| Concrete | 41.5%                                    |                              |          |      |      |

Certainly, other practices under the umbrella of front end planning are also important. However, the above identified practices are statistically significant with improved concrete productivity among the sampled projects. The BM&M's average scores of each significant practice involved in front end planning is shown in Figure 2-1, which gives an idea of how participating companies stand in relation to their peers.

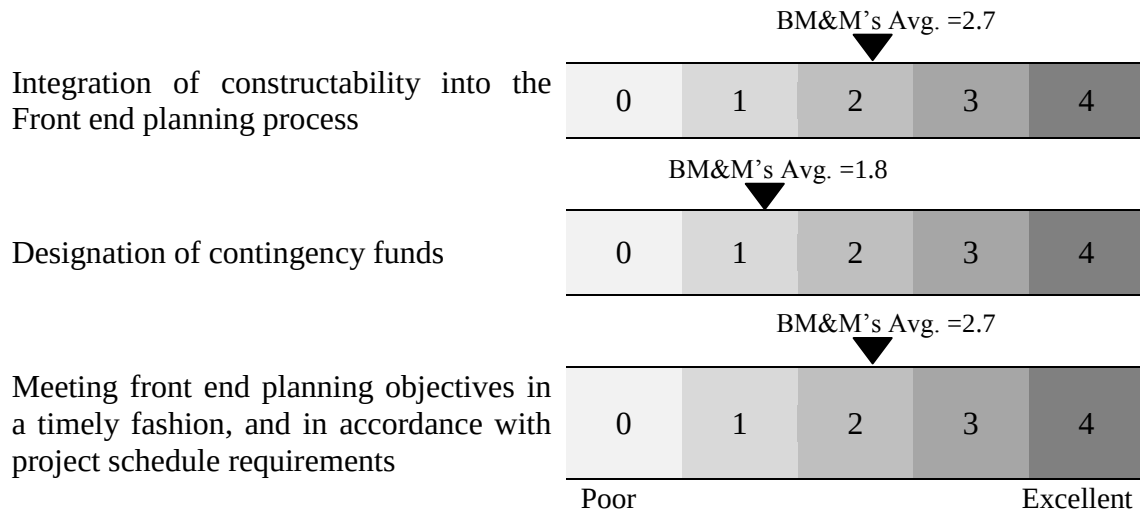


**Figure 2-1.BM&M's Average Scores of Critical Practices involved in Front End Planning**

## 2.2 Team Building

CII defines team building as a formal project-focused process that builds and develops shared goals, interdependence, trust and commitment, and accountability among team members,

as well as improving team members' problem-solving skills. Using the BM&M's data, RT 252 identified the inclusion of major suppliers in the team building process is of significance to the concrete craft productivity. This finding intuitively makes sense, since concrete suppliers play an important role in ensuring the timely availability of concrete at construction sites. Statistical analysis shows that the composite team building index developed based upon the identified practice has a positive relationship with craft productivity (Table 2-2). Approximately 50.6% difference in raw productivity was observed on the projects stressing more on major suppliers' involvement in team building process.

**Table 2-2. Team Building versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                         |          |      |      |
|----------|------------------------------------------|-------------------------|----------|------|------|
|          | High Level Team Building                 | Low Level Team Building | $\Delta$ | t    | Sig. |
| Concrete | 3.1                                      | 4.5                     | -1.4     | -3.1 | .00  |
|          | Percent Difference in Labor Productivity |                         |          |      |      |
|          | Team Building                            |                         |          |      |      |
| Concrete | 50.6%                                    |                         |          |      |      |

Figure 2-2 shows that, among the BM&M participating companies, only 18.9% of them included major suppliers in the team building process, which is relatively low. However, statistical analyses showed including major suppliers in the team building process is significantly correlated with better concrete craft productivity.

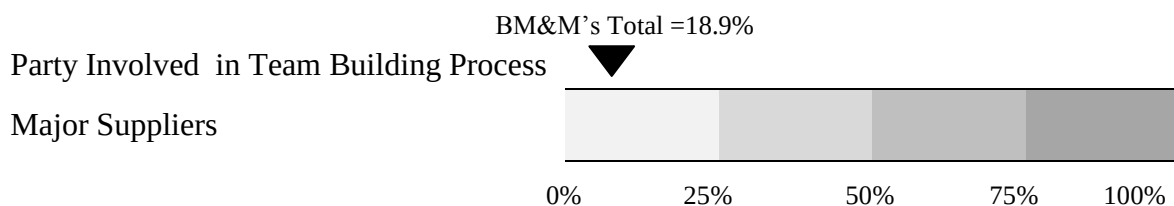


**Figure 2-2. BM&M's Percentage of Sampled Projects include Major Suppliers in Team Building Process**

## 2.3 Change Management

CII addresses change management as the process of incorporating a balanced change culture of recognition, planning, and evaluation of project changes in an organization to effectively manage project changes. RT 252 identified the following practices to be correlated to the improved concrete craft productivity:

- 1) Clearly specifying change management process in the project contract;
- 2) Ensuring that key project personnel (from both owner and contractor teams) understand the change management process;
- 3) Proactively managing changes on detailed engineering/design;
- 4) Requiring major changes (i.e. those that exceeded a specified project threshold) to go through a formal change justification procedure;
- 5) Requiring owner authorization before implementation of major changes; and
- 6) Communicating change information to key project participants.

RT 252 identified a significant relationship between change management and concrete craft productivity. It is noted that the projects with a high-level of change management implementation obtained 49.5% better craft productivity compared to a low-level use projects. (See Table 2-3.)

**Table 2-3. Change Management versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                             |          |      |      |
|----------|------------------------------------------|-----------------------------|----------|------|------|
|          | High Level Change Management             | Low Level Change Management | $\Delta$ | t    | Sig. |
| Concrete | 4.3                                      | 5.8                         | -1.5     | -1.9 | .05  |
|          | Percent Difference in Labor Productivity |                             |          |      |      |
|          | Change Management                        |                             |          |      |      |
| Concrete | 49.5%                                    |                             |          |      |      |

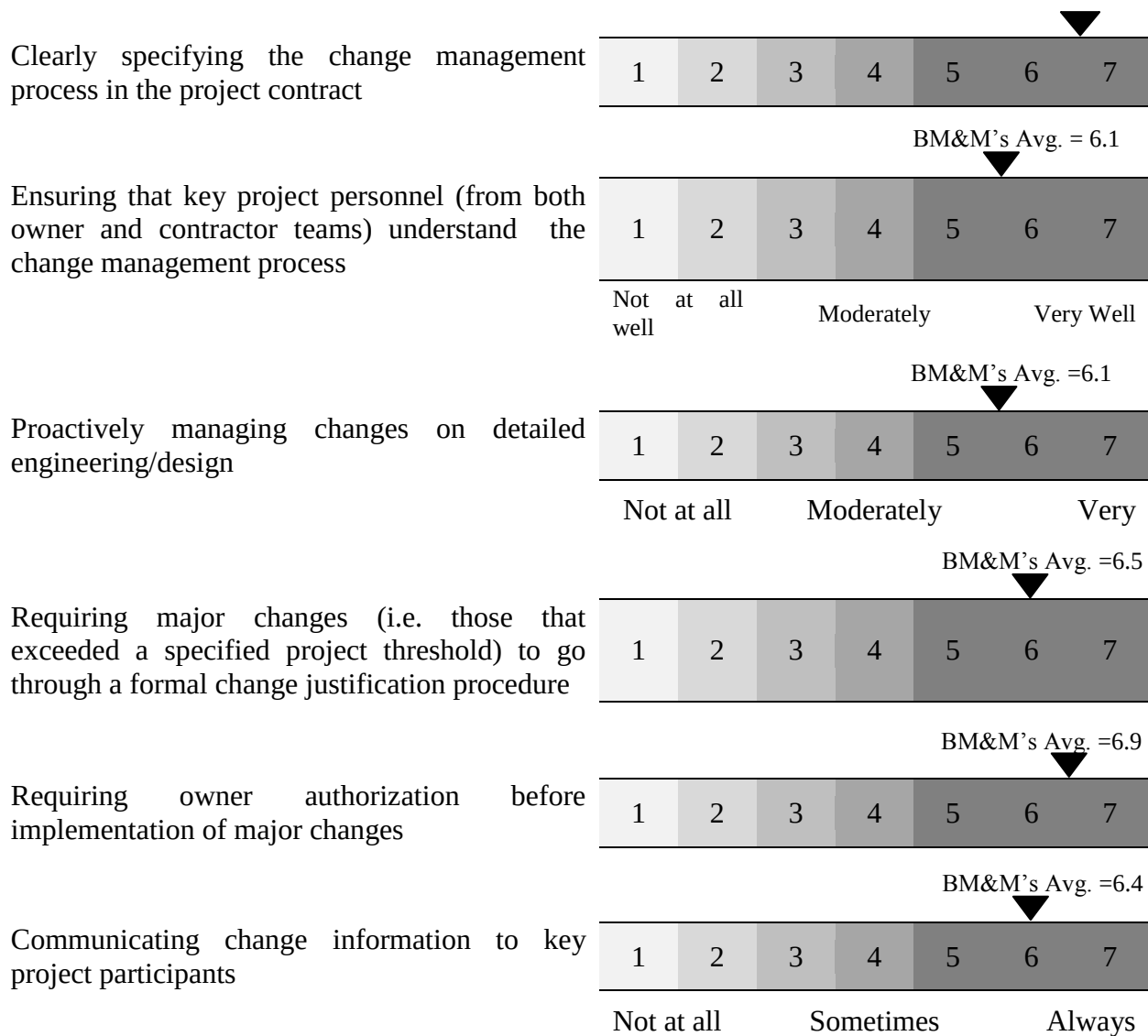


**Figure 2-3. BM&M's Average Scores of Critical Practices involved in Change Management**

The BM&M committee uses a seven-point scale to measure the level of a project's performance on practices associated with the change management program. Figure 2-3 presents the average performance of the sampled project on the critical practices involved the change management that were statistically correlated to improved concrete productivity.

## 2.4 Materials Management

The CII BM&M program addresses 12 practices involved in a materials management program. Obviously, each of the practices under a materials management program is essential to a project's overall productivity, however, RT 252 identified seven practices statistically related to improved concrete productivity, including the following:

- 1) Integration of designated materials management organization across project team;
- 2) Effective site materials management during the construction phase;
- 3) Effective materials tracking and reporting system;
- 4) Effective purchasing plans & procedures over the life of the project;
- 5) Effective receipt and inspection procedures for critical materials and equipment;
- 6) Adequate pre-qualification process for securing the appropriate suppliers of major equipment and materials; and
- 7) Materials management plan utilizing quality management practices.

As a result, a composite practice use index was developed based on the seven practices. Using the same criteria as already described, projects scoring above five percent of the overall median of the new practice use indices were classified as having a high level use, and projects scoring below five percent of the median were otherwise classified as having a low level use.

According to Table 2-4, projects with a high level of materials management program implementation can save 1 time unit per unit of installed quantity compared to low-level implementers. A percentage difference in raw productivity was also calculated between low- and high-level implementers, a measurement that indicated that high-level implementers among the sample projects were 44.5% more productive than their counterparts. (See Table 2-4.)

**Table 2-4. Material Management versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                                |          |      |      |
|----------|------------------------------------------|--------------------------------|----------|------|------|
|          | High Level Materials Management          | Low Level Materials Management | $\Delta$ | t    | Sig. |
| Concrete | 3.7                                      | 4.7                            | -1.0     | -1.8 | .06  |
|          | Percent Difference in Labor Productivity |                                |          |      |      |
|          | Materials Management                     |                                |          |      |      |
| Concrete | 44.5%                                    |                                |          |      |      |

The CII BM&M committee uses a 0-4 scale to measure the performance on the specific practices in the materials management program. A “0” rating indicates not implementing a specific practice at all on a project, and “4” indicates implementing a practice fully on a project. Figure 2-4 describes the average performance of the BM&M sampled projects on the practices that were found statistically correlated to improved concrete craft productivity.

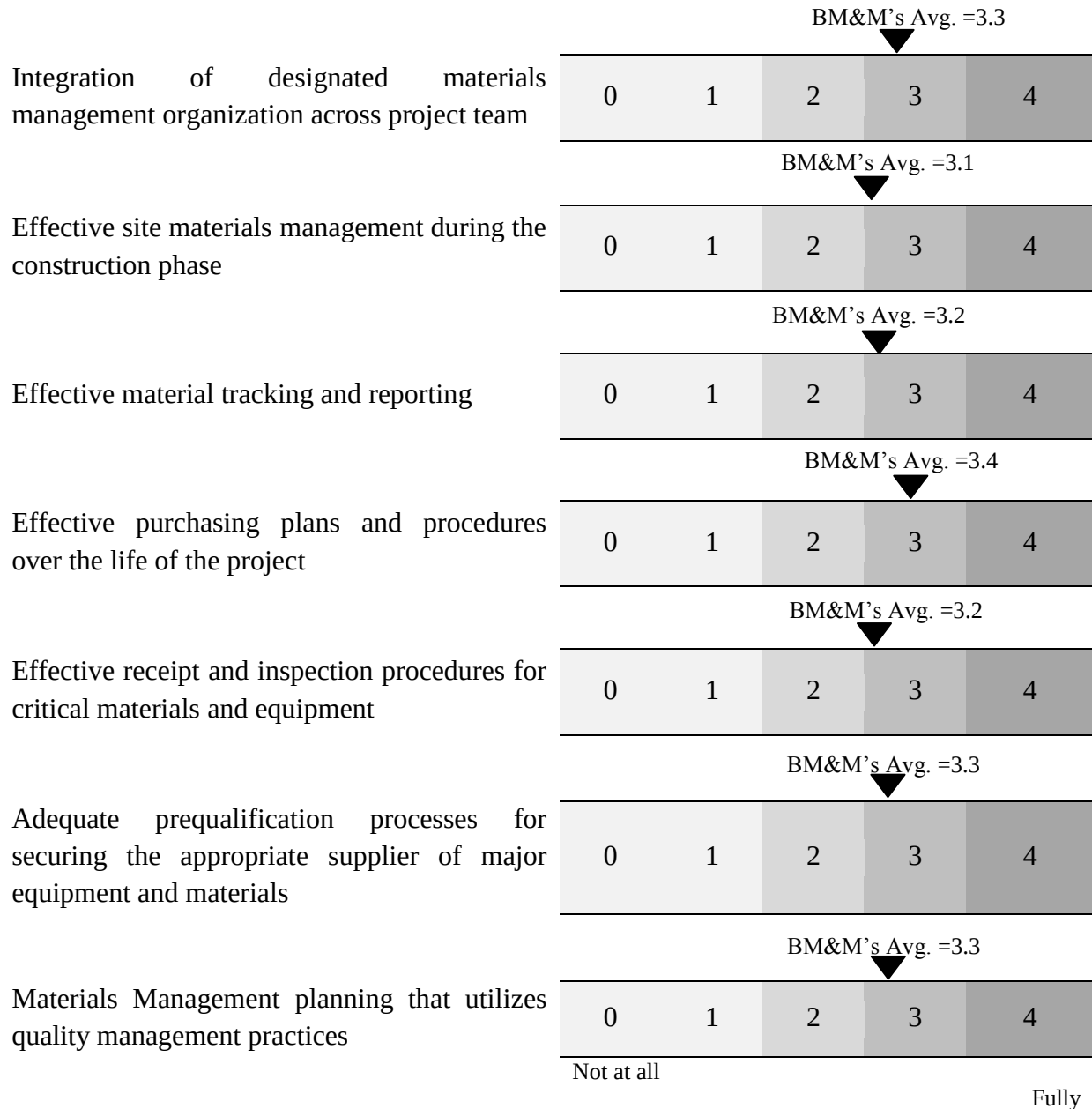


**Figure 2-4. BM&M's Average Score on Critical Materials management Practices**

## 2.5 Safety

RT 252 identified safety as one of the most important productivity drivers in both Phase I and Phase II among mechanical and electrical trades. RT 252 identified that safety continues this trend by having a strong correlation with concrete productivity. Zero accident techniques are one

of CII's best practices addresses safety in 18 different specific areas. RT 252 identified eight critical practices out of the current 18 zero accident practices to be highly correlated with concrete productivity and were included to develop composite safety index:

- 1) Prioritization of Safety as a topic at pre-construction and construction meetings;
- 2) Performance of safety audits by corporate safety personnel;
- 3) Utilization of safety performance as a criterion of contractor/subcontractor selection;
- 4) Formal investigation of near misses;
- 5) Requirement of pre-employment substance abuse tests for contractor employees;
- 6) Performance of random alcohol and drugs screening for contractor employees; and
- 7) Substance abuse tests after accidents.

However, it should be stressed that all zero accident practices are necessary to preserve the health and safety of everyone on a construction jobsite. RT 252 quantified the difference in both normalized and raw concrete productivity between the low and high-level projects. Projects with better safety implementation showed 38.6% better concrete craft productivity than their counterparts. (See Table 2-5.)

**Table 2-5. Safety versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                  |          |      |      |
|----------|------------------------------------------|------------------|----------|------|------|
|          | High Level Safety                        | Low Level Safety | $\Delta$ | t    | Sig. |
| Concrete | 3.0                                      | 4.3              | -1.3     | -2.5 | .01  |
|          | Percent Difference in Labor Productivity |                  |          |      |      |
|          | Safety                                   |                  |          |      |      |
| Concrete | 38.6%                                    |                  |          |      |      |

Figure 2-5 illustrates the average scores of the BM&M sampled projects on the identified seven critical safety practices.

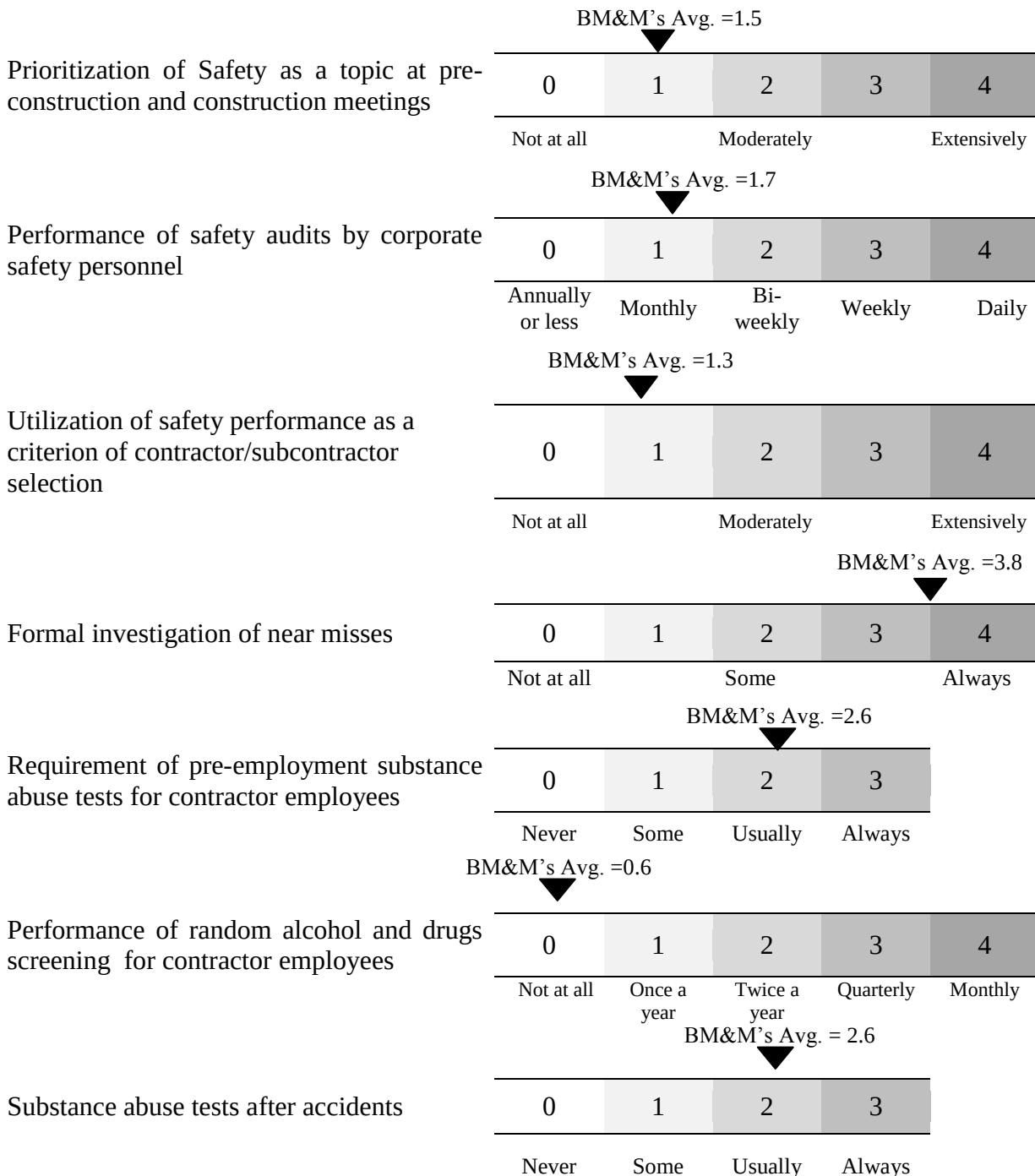


**Figure 2-5. BM&M's Average Scores of Critical Safety Practices**

## 2.6 Integration of Information Systems

CII defines integration as the sharing of information among project participants to support effective execution. The integration of information systems index quantifies the level of implementation on 13 work functions, including business planning and analysis, conceptual definition and design, project (discipline) definition and facility design, supply management, coordination system, communications system, cost system, schedule system, quality system, off-site/pre-construction, construction, as-built documents, and facility start-up and life cycle support. CII RT 252 identified three work functions: 1) project (discipline) definition and facility design, 2) schedule system, and 3) facility start-up and life cycle support are statistically correlated with improved concrete craft productivity. Statistical analysis shows a significant relationship between projects' high level use of integration information systems and better productivity among the projects' concrete trades. The projects with more integration of the three work functions discussed above experienced a productivity advantage over the projects with less integration among the same functions. (See Table 2-6.)

**Table 2-6. Integration of Information Systems versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity                 |                                              |          |      |      |
|----------|-----------------------------------------------|----------------------------------------------|----------|------|------|
|          | High Level Integration of Information Systems | Low Level Integration of Information Systems | $\Delta$ | t    | Sig. |
| Concrete | 4.1                                           | 5.3                                          | -1.2     | -2.6 | .01  |
|          | Percent Difference in Labor Productivity      |                                              |          |      |      |
|          | Integration of Information Systems            |                                              |          |      |      |
| Concrete | 33.4%                                         |                                              |          |      |      |

A five-point scale (from 1-5) was used to define the level of integration of information system on each work function. “1” indicates none/minimal use, and “5” indicates full use. Detailed descriptions were provided in the surveys that BM&M committee used to collect the data. Figure 2-6 illustrates the BM&M’s average level of integration application across the work

functions identified to be correlated to concrete productivity. The level of application across the three work functions was around a moderate level among the sampled projects.

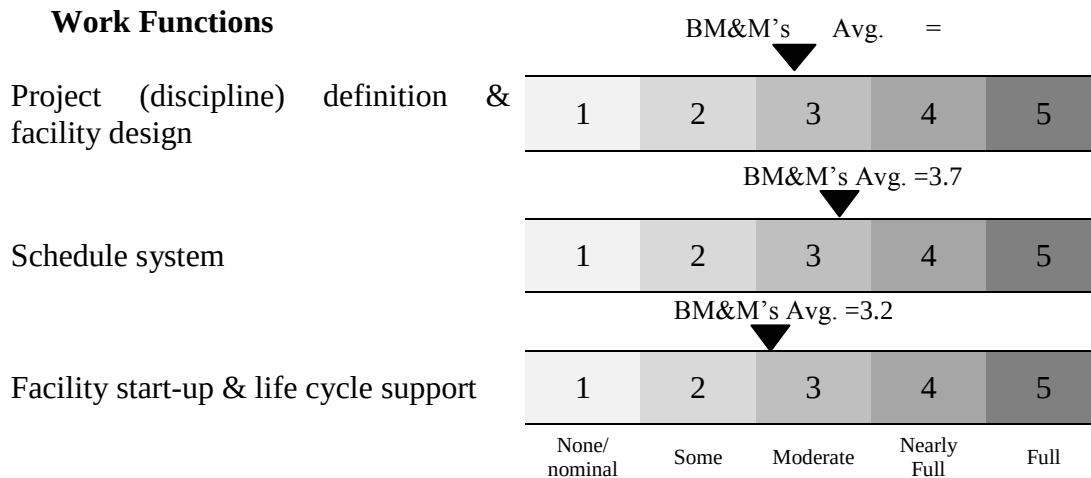


**Figure 2-6. The BM&M's Average Level of Integration Use across Work Functions**

## 2.7 Constructability

Constructability is the optimal integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives. Among the seven specific practices addressed by the CII BM&M survey, RT 252 identified that tracking lesson learned and saving/effects on projects due to a constructability program is correlated with concrete craft productivity. Statistical analyses shows that the projects with better implementation experienced 31.1% better productivity than the projects with little implementation. (See Table 2-7.)

**Table 2-7. Constructability versus Concrete Craft Productivity**

| Trade    | Normalized Labor Productivity            |                            |          |      |      |
|----------|------------------------------------------|----------------------------|----------|------|------|
|          | High Level Constructability              | Low Level Constructability | $\Delta$ | t    | Sig. |
| Concrete | 3.5                                      | 4.6                        | -1.1     | -2.0 | .04  |
|          | Percent Difference in Labor Productivity |                            |          |      |      |
|          | Constructability                         |                            |          |      |      |
| Concrete | 31.1%                                    |                            |          |      |      |

Among the BM&M sampled projects, the average performance on tracking lessons learned from previous constructability program was around moderate level. (See Figure 2-7.)

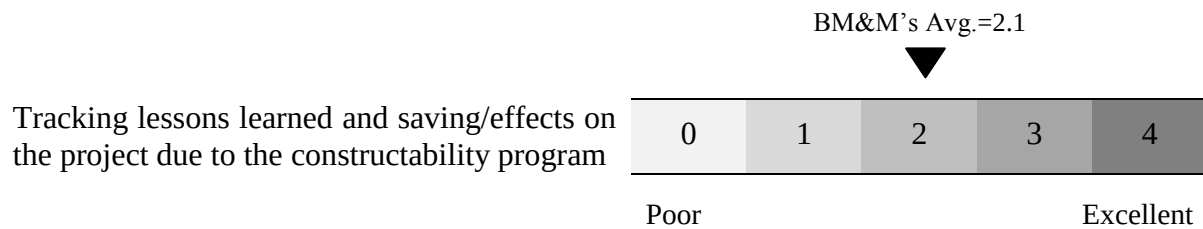


**Figure 2-7. BM&M's Average Performance on Tracking Lessons learned from Previous Constructability Program**

## 2.8 Summary

Overall, this chapter identified a number of project practices as described in the BM&M survey are significantly correlated with improved productivity in the concrete trades.

Table 2-8 summarizes the significant practices from these analyses. It should be stressed that a number of practices within these areas such as materials management and safety, were found to lack a significant relationship with improved productivity, but should be implemented regardless. For example, all CII safety practices are associated with improved safety performance, but not necessarily with improved productivity. Companies should carefully review the practices in Table 2-8, and if necessary prioritize their resources on a project.

**Table 2-8. List of Significant Practices for Each Management Program**

| <b>Front end Planning</b>                                  |                                                                                                                                        |
|------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| 1                                                          | Integration of constructability feedback into front end planning;                                                                      |
| 2                                                          | Designation of contingency funds;                                                                                                      |
| 3                                                          | Meeting front end planning objectives in a timely fashion, and in accordance with project schedule requirements                        |
| <b>Team Building</b>                                       |                                                                                                                                        |
| 1                                                          | Major suppliers involved in the team building process                                                                                  |
| <b>Change Management</b>                                   |                                                                                                                                        |
| 1                                                          | Clearly specifying change management process in the project contract                                                                   |
| 2                                                          | Ensuring that key project personnel (from both owner and contractor teams) understand the change management process                    |
| 3                                                          | Proactively managing changes on detailed engineering/design                                                                            |
| 4                                                          | Requiring major changes (i.e. those that exceeded a specified project threshold) to go through a formal change justification procedure |
| 5                                                          | Requiring owner authorization before implementation of major changes                                                                   |
| 6                                                          | Communicating change information to key project participants                                                                           |
| <b>Material Management</b>                                 |                                                                                                                                        |
| 1                                                          | Integration of designated materials management organization across project team                                                        |
| 2                                                          | Effective site materials management during the construction phase                                                                      |
| 3                                                          | Effective materials tracking and reporting system                                                                                      |
| 4                                                          | Effective purchasing plans & procedures over the life of the project                                                                   |
| 5                                                          | Effective receipt and inspection procedures for critical materials and equipment                                                       |
| 6                                                          | Adequate pre-qualification process for securing the appropriate suppliers of major equipment and materials                             |
| 7                                                          | Materials management plan utilizing quality management practices                                                                       |
| <b>Safety</b>                                              |                                                                                                                                        |
| 1                                                          | Prioritization of Safety as a topic at pre-construction and construction meetings                                                      |
| 2                                                          | Performance of safety audits by corporate safety personnel                                                                             |
| 3                                                          | Utilization of safety performance as a criterion of contractor/subcontractor selection                                                 |
| 4                                                          | Formal investigation of near misses                                                                                                    |
| 5                                                          | Requirement of pre-employment substance abuse tests for contractor employees                                                           |
| 6                                                          | Performance of random alcohol and drugs screening for contractor employees                                                             |
| 7                                                          | Substance abuse tests after accidents                                                                                                  |
| <b>Integration of Information Systems (Work Functions)</b> |                                                                                                                                        |
| 1                                                          | Project (discipline) definition & facility design                                                                                      |
| 2                                                          | Schedule system                                                                                                                        |
| 3                                                          | Facility start-up & life cycle support                                                                                                 |
| <b>Constructability</b>                                    |                                                                                                                                        |
| 1                                                          | Track lessons learned and saving/effects on this project due to the constructability program                                           |

# **CHAPTER 3 . CONCRETE CONSTRUCTION PRODUCTIVITY INNOVATIONS**

The Rework Reduction Program is an innovation that can dramatically change construction processes and thereby improve construction productivity across multiple trades. In tandem with its effort to develop the RRP, RT 252 also analyzed other potential breakthrough solutions specific to the concrete trades. These breakthroughs are described below.

## **3.1 Grade 100 Steel Reinforcement**

### **3.1.1 Background**

The emergence of high strength steel in the form of Grade 100 steel reinforcing bars has recently made its way onto the construction scene. This new technology has now been recognized in industry standards through the addition of ASTM A1035. The major difference in Grade 100 steel and Grade 60 steel lies in the yield strength of these materials. The “Grade” of each type of steel is its yield strength, which is in ksi (1,000 pounds per square inch). The yield strength of a material is approximately the stress at which the material will be subjected to permanent deformation upon further loading. Figure 3-1 (American Concrete Institute, 2010) shows the yield strength of several grades of steel, among which Grade 60 and Grade 100 are included.

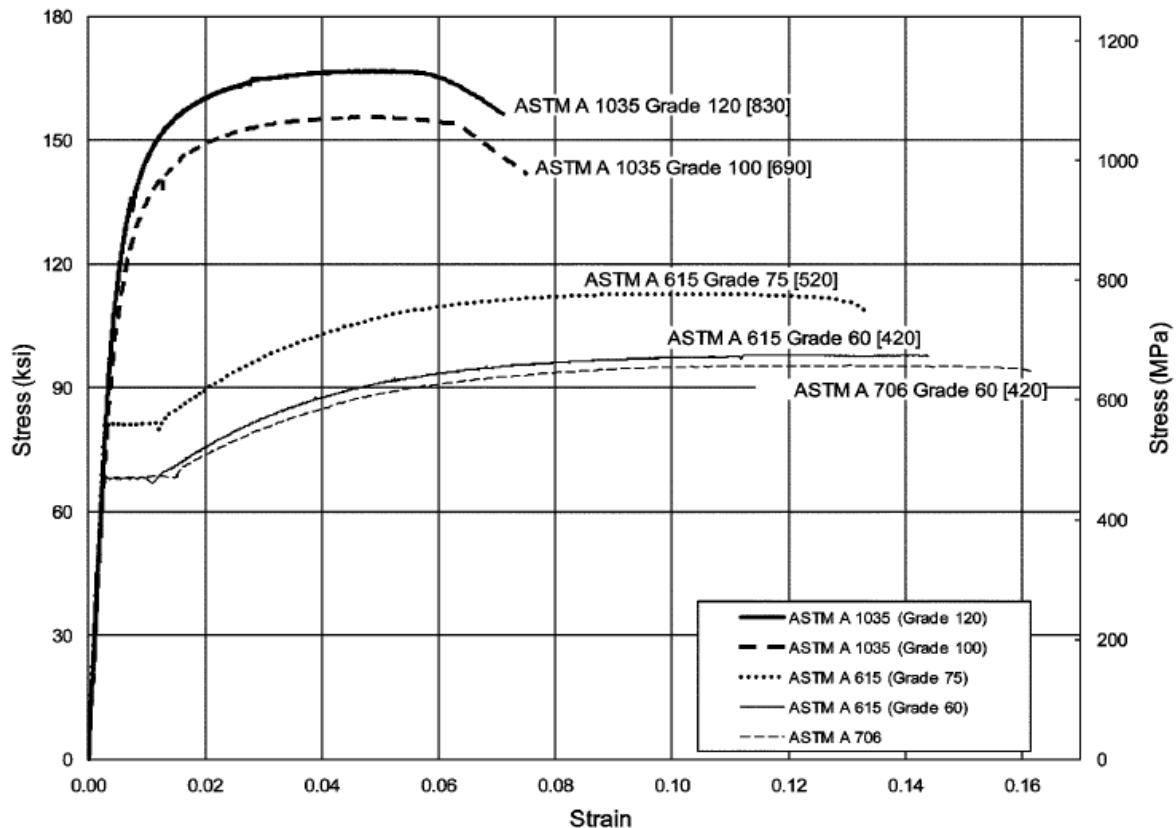


**Figure 3-1. Stress-Strain Curves for Various Grades of Steel (American Concrete Institute, 2010)**

From this figure, the much higher stress levels that Grade 100 steel can handle compared to Grade 60 steel are illustrated. One potential drawback, however, of Grade 100 steel can also be seen; the material ruptures at a much lower strain level compared to Grade 60 steel. This strain is the amount of “give” the materials have before the sharp drops on the figure that represent material failures. Since Grade 100 steel does not have as much strain before failing compared to Grade 60 steel, it is a safety concern in structural design since there would be fewer warning signs before a potential structural failure. These material properties create both positive and negative aspects regarding a decision to use Grade 100 steel over Grade 60 steel.

While Grade 60 steel is more ductile than Grade 100 steel, all commonly used steel in buildings are ductile materials. Concrete is a strong material regarding compression, but is weak in tension. Adding structural steel to concrete uses the high tensile strength of steel to add tensile strength to the concrete member being reinforced. Reinforced concrete members can therefore handle loads in which the member is subjected to both tension and compression forces. In theory, a higher grade of steel can provide for a stronger reinforced concrete member. One of the issues regarding the use of high strength steel reinforcement is that the high strength steel may be less ductile than the traditional strength steel. If Grade 100 steel is less ductile (more brittle) compared to Grade 60 steel, then this must be accounted for in the design. This issue will be addressed later in the report. Regarding reinforcing bars in concrete members, a higher grade steel may be able to replace a lower grade steel such that less steel is required to reinforce the concrete member to the same degree. In some cases, this may even result in a more cost effective design if enough steel can be reduced in the beam design. This idea will be further analyzed in the remainder of the report.

MMFX Steel Corporation is currently the sole manufacturer of ASTM A1035 Grade 100 steel. This steel is commercially available via distribution centers located throughout the United States in the form of #3 to #14 sized reinforcing bars (MMFX, 2010). The size of reinforcing bars, up to #10 bars, is given as how many eighths of an inch the bar's diameter is. For example a #8 reinforcing bar is one inch in diameter and a #4 reinforcing bar is one-half inch in diameter. Even with its higher strength properties, Grade 100 steel reinforcing bars can still be bent in the same fashion as Grade 60 bars. The procedures and requirements for bending Grade 100 steel reinforcing bars conform to the specifications in ASTM A615 and A1035 (MMFX, 2010). For #3 to #5 bars the pin diameter for bending tests is 3.5d; 5d for #6 to #8; 7d for #9 to #11; and 9d

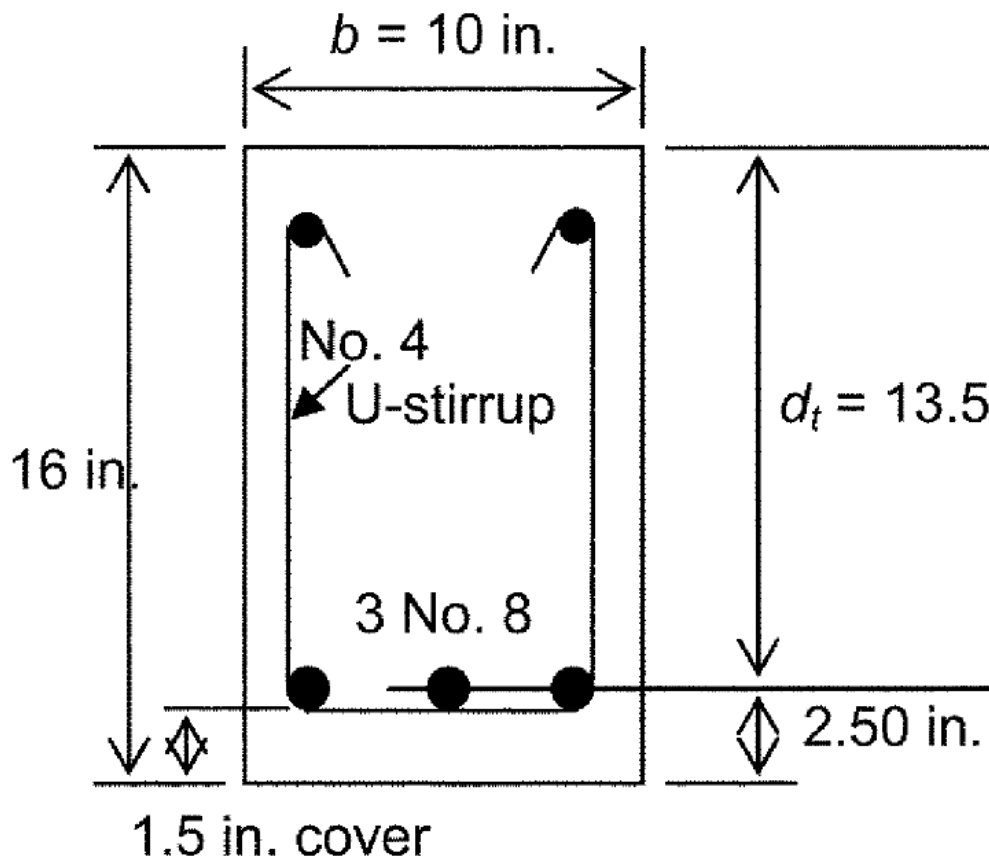
for #14 and #18 (MMFX, 2010). There have already been a handful of projects that have used Grade 100 steel. The majority of these projects are found in areas where high seismic load requirements are found. In these areas, a common problem is that the increase in structural strength requirements for the seismic design loads results in heavy reinforcing bar congestion (Humphreys and Risser, 2008). This congestion can make rebar installation and concrete placement very difficult; Grade 100 reinforcing bars have already alleviated some of these issues on such projects. More specifically, reinforcing bar congestion in beam/column intersections have been addressed using Grade 100 steel bars. In this report, further potentially beneficial uses of Grade 100 reinforcing steel will be analyzed in regards to more commonplace applications on construction sites regarding reinforced concrete beams.

### 3.1.2 Scope

There are several assumptions that have been established for this research. First, while dealing with only reinforced concrete beams, this design category is further broken down to only looking at uniformly loaded reinforced concrete beams. This assumption will limit the applications of this research such that beams subjected to other forms of loading, such as a point load, will not be applicable for all analyses performed. This limitation is specifically necessary for the beam length analysis. In this analysis, the effects of a uniform load on required reinforcement are analyzed as the beam length increases. Additional assumptions have been made regarding the spacing of the reinforcing bars in the designs. Firstly, the reinforcing bar ties used for this analysis will only consist of size #4 (0.5 inch diameter ties). Secondly, the clearance from the bottom of the beam to the bottom of the rebar tie in the tension zone will be set at 1.5 inches. This number will be added in when determining the distance from the bottom of the

beam to the centroid of the tension reinforcement. Other figures used to determine this distance will be the diameter of the rebar tie, diameter of the rebar, and vertical clearance between reinforcing bars in cases where more than one reinforcement layer is used. A minimum vertical spacing of one inch will be used in those instances. Also, when compression reinforcement is necessary, a clearance of 1.5 inches will be used from the top of the beam to the rebar tie. The following Figure 3-2 shows an example beam similar to those that will be used for the analyses that will follow:

**Figure 3-2. Example Beam Design (American Concrete Institute, 2010)**



### 3.1.3 Calculations

#### 3.1.3.1 Calculating the design moment strength from the area of steel reinforcement

The nominal moment strength and design moment strength can be determined for a beam with known dimensions and known area of steel through the simplified process, which was created by Mast et al. in 2008. The area of steel is input into this process through specifying a certain amount of a certain size bar. From this, the nominal moment strength and design moment strength is determined. Then the amount of reinforcing steel is verified to be an adequate amount in this process.

#### ***Define the rectangular concrete stress distribution for a compression-controlled beam***

Since this process is for checking a known design, the nominal depth and area of steel are already known for this beam. One assumption must be made at the start of the simplified method, which is that the beam is either compression-controlled or tension-controlled. Initially, it is assumed that the beam is compression-controlled. The assumption that the beam is compression-controlled means that it must be proven that  $\epsilon_s < \epsilon_y$ . The term  $\epsilon_y$  (yield strain of steel) can be found using the following equation:

$$\epsilon_y = \frac{f_y}{E_s}$$

$f_y = \text{yield strength of steel}$   
 $E = \text{modulus of elasticity of steel}$

The values necessary to calculate  $\epsilon_y$  are known. To prove that  $\epsilon_s < \epsilon_y$ , the actual value of  $\epsilon_s$  must be calculated. The following equations are used to do this:

$$\begin{aligned} T &= A_s E_s \epsilon_s \\ C &= 0.85 f'_c b a \\ \epsilon_s &= \frac{d_t - c}{c} * \epsilon_{cu} \end{aligned}$$

$$c = \frac{a}{\beta_1}$$

$$\varepsilon_{cu} = \text{strain at which concrete crushes} = 0.003$$

$$T = C$$

Using the equilibrium relationship between T and C, and with substitution, a quadratic equation can be formulated in terms of “a” and solved.

### ***Net tensile strain and strength reduction factor***

From following the equations above,  $\varepsilon_s$  can now be calculated. Our initial assumption that  $\varepsilon_s < \varepsilon_y$  can now be checked. If it checks, then the section is in fact compression controlled. If the  $\varepsilon_s < \varepsilon_y$  relationship is not true, then the process should be restarted assuming that the section is tension-controlled. This process immediately follows this section. For  $\varepsilon_s < \varepsilon_y$  true, the strength reduction factor can now be determined using the following rule for Grade 100 reinforcing steel designs:

$$0.65 \leq (\phi = 0.45 + 50\varepsilon_t) \leq 0.9$$

The strength reduction factor may change for different Grade 100 reinforcing steel designs depending on whether the design is within the tension-controlled limits, compression-controlled limits, or transition zone. Since this beam section was compression-controlled, a strength reduction factor of 0.65 is used.

Figure 3-3 illustrates the relationship between the strength reduction factor and strain for a beam with Grade 100 reinforcement:

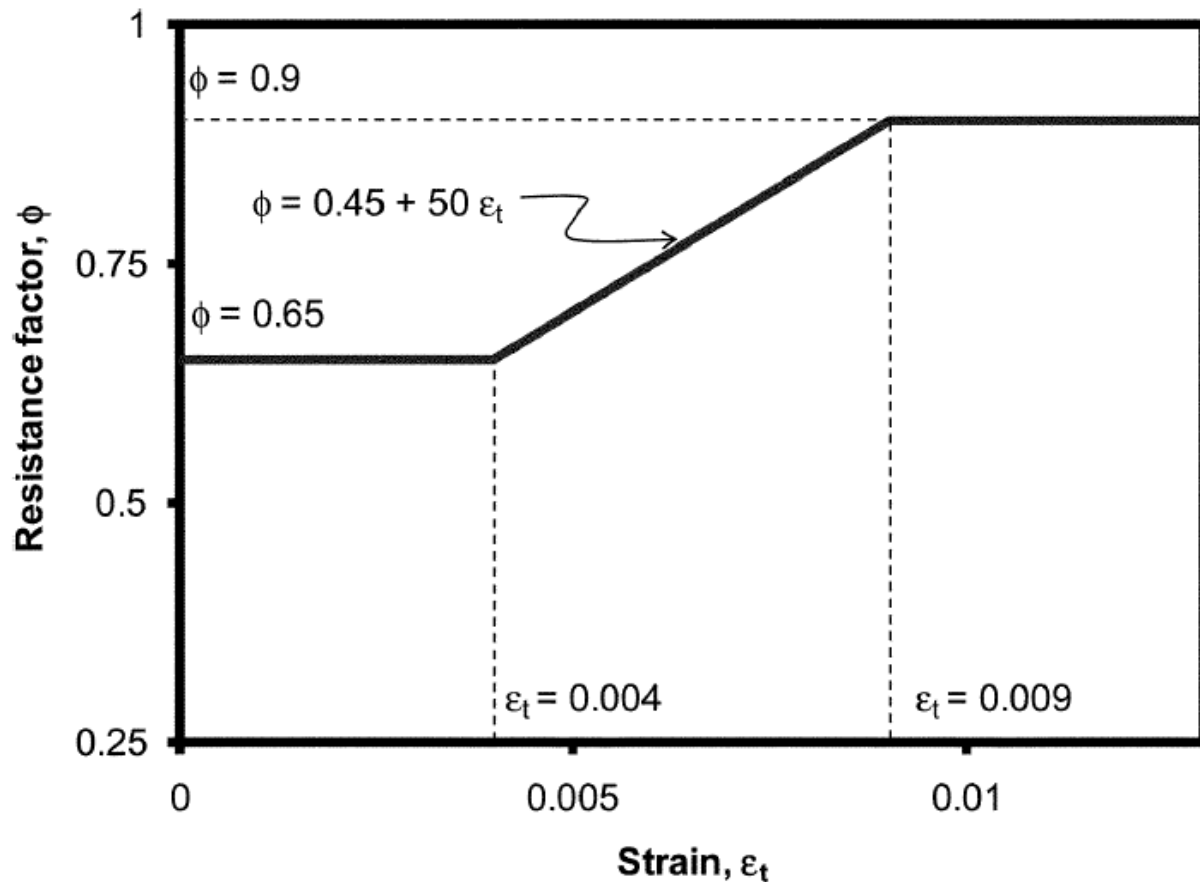


**Figure 3-3. Relationship between strength reduction factor and strain for Grade 100 steel (American Concrete Institute, 2010)**

From the figure above, it is found that if  $\epsilon_t$  is greater than 0.009, then it is in the tension controlled section and a strength reduction factor of 0.85 is used. If  $\epsilon_t$  is less than 0.004, then it is in the compression controlled section and a strength reduction factor of 0.65 is used. For the strains between 0.004 and 0.009, it is in the transition phase and an adjusted strength reduction factor is used (from the equation above).

Beams designed with Grade 60 steel simply use the 0.004 strain as a dividing line between the compression-controlled section and a tension-controlled section; the strength reduction factor is either 0.65 or 0.9. In other words, there is no transition phase used for Grade 60 designs.

### ***Nominal moment strength and design moment strength***

$$M_n = A_s E_s \epsilon_s \left( d_t - \frac{a}{2} \right)$$

From this nominal moment strength equation the design moment strength can be determined by multiplying it by the strength reduction factor that was previously determined.

### ***Reinforcement Check***

To make sure that the amount of reinforcement chosen is adequate, the minimum required area of steel needs to be calculated and compared.

$$A_{s,min} = \frac{3\sqrt{f'_c}}{f_y} * b_w d \geq \frac{200b_w d}{f_y}$$

The larger of these two values is used as the minimum required area of steel. The area of steel that was provided for the design must be greater than this minimum value for the design to be satisfactory.

### ***Differences in simplified method for a tension-controlled beam***

As stated previously, if the section was assumed to be compression-controlled and was proven not to be from the above process, then the following process should be followed assuming that the section is tension-controlled. That is,  $\epsilon_s > \epsilon_y$  is assumed to be true now. The value of  $\epsilon_y$  is calculated in the same way as for compression-controlled sections. The differences in equations are as follows:

$$T = A_s f_y$$
$$a = \frac{T}{0.85 f'_c b}$$

From here, the values of  $c$  and  $\epsilon_s$  can be determined and the assumption that  $\epsilon_s > \epsilon_y$  can be checked. For Grade 100 designs, if  $\epsilon_s$  is greater than 0.004 but less than 0.009, then the section is in the transition zone between compression-controlled and tension-controlled. If  $\epsilon_s$  is greater than 0.009, then it is in the compression zone. To determine the strength reduction factor here, follow the process shown in Figure 3-3 above. For both of these cases, the nominal moment strength and design moment strength are determined as follows:

$$M_n = A_s f_y \left( d_t - \frac{a}{2} \right)$$

The design moment strength is simply the nominal moment strength multiplied by the strength reduction factor.

### 3.1.3.2 Calculating the amount of reinforcement needed from design moment strength

The following equations (American Concrete Institute, 2010; Portland Cement Association, 2002) are used to calculate the required area of steel reinforcement for beams with known dimensions and loadings. The differences in the calculations between Grade 60 steel and Grade 100 steel are noted where applicable.

#### ***Design moment strength ( $\phi M_n$ )***

$$\phi M_n = \frac{w_u * l_n^2}{8}$$

$w_u = \text{factored load (kips/ft.)}$   
 $l_n = \text{nominal length (ft.)}$

The factored load is a uniformly distributed load that combines factored loads that are designed into the beam. These loads can include, but are not limited to, live loads, dead loads, and ice/snow loads.