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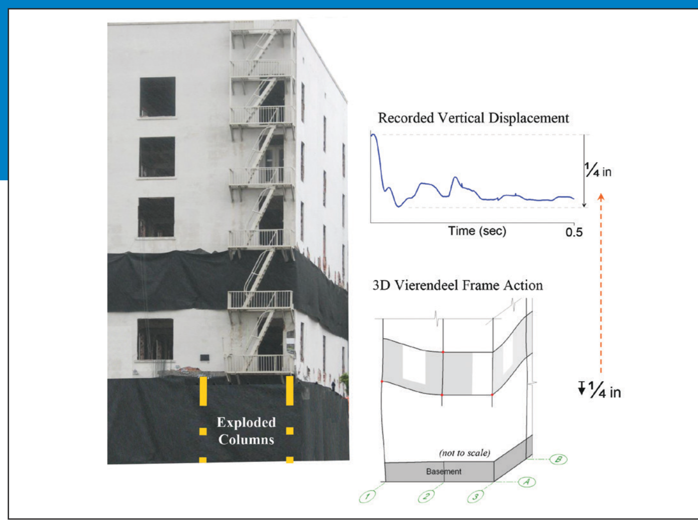

Structural Integrity and Resilience

SP-309

Editors:
Mehrdad Sasani and Sarah Orton

American Concrete Institute
Always advancing

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Preface

The need for structural integrity has been recognized ever since the 1968 failure of the Ronan Point Apartment building. Improvements to the ACI code in 1989 required additional reinforcement for structural integrity, however those requirements were based on generally good building practices with little research or analysis to support them. However, since the disproportionate failure of the Murrah Federal building in Oklahoma City, these requirements have received renewed interest and new research conducted. More recently, and primarily due to the aftermath of natural and manmade disasters, the need for designing buildings that are resilient against various hazards has been recognized.

While most of the latest research does not directly analyze the efficacy of the structural integrity requirements, it does consider the overall collapse resistance and robustness of reinforced concrete buildings. Research using field experiments conducted in the last decade indicates that reinforced concrete structures are generally robust against local damage like single column removal. Although structural integrity requirements have been included in ACI 318 since 1989, there still exists areas of improvement. For example, recent laboratory experiments show that flat plate structures may still be vulnerable due to the high likelihood of progressive punching shear failures. Furthermore, for structures designed and built without structural integrity provisions, new research highlights ways to improve their robustness and collapse resistance. Finally, improved analysis models and predictions on the likelihood of collapse lead to better assessment of the risks of collapse.

ACI Committee 377 sponsored two sessions during the Fall 2014 ACI convention in Washington, DC to highlight the importance of structural integrity and resilience of reinforced concrete and precast/prestressed structures subjected to extreme loading conditions. The sessions sought papers on topics including improving the structural integrity of structures, minimum level of required integrity, integrity of precast/prestressed structures, performance-based structural integrity and resilience, infrastructure resilience, issues and new developments in modeling, and assessment of existing structures. Both experimental and analytical investigations were presented. The sessions presented 10 papers covering the design of reinforced concrete buildings against progressive collapse, evaluation of NYC code provisions, analysis and experimental testing of post-tensioned and precast/prestressed structures, methods to improve collapse resistance, and probabilistic analysis of collapse.

This special publication includes eight papers that were presented during the sessions. The papers are alphabetically ordered based on the last names of the first authors.

Editors

Sasani, M., and Orton, S.

TABLE OF CONTENTS

SP-309—1
A Simple Method of Enhancing the Robustness of R/C Frame Structures ....1.
Authors: Yihai Bao, H.S. Lew, Joseph A. Main and Fahim Sadek

SP-309—2
New York City Building Code Flat Plate Integrity Provisions..2.
Authors: Ramon Gilsanz, Karl Rubenacker, and Jennifer Lan

SP-309—3
Response of a Post-Tensioned Floor Following a Column Loss ....3.
Authors: Leila Keyvani and Mehrdad Sasani

SP-309—4
Uncertainties in Predicting Structural Disproportionate Collapse ....4.
Authors: Shalva Marjanishvili and Serdar Astarlioglu

SP-309—5
Post-Punching Capacity of Flat-Plate Floor Systems ....5.
Authors: Sarah Orton, Ying Tian, Zhonghua Peng, and Jinrong Liu

SP-309—6
Recent Progress in Understanding of Load Resisting Mechanisms...........................6.
for Mitigating Progressive Collapse
Authors: Kai Qian, Bing Li, and Ying Tian

SP-309—7
Assessment of Urban Building Complexes Subjected to Natural and .... 7.
Man-Made Hazards
Authors: Malte von Ramin, Alexander Stolz, Oliver Millon, and Tassilo Rinder

SP-309—8
Risk Assessment of Reinforced Concrete Buildings Against ....8.
Progressive Collapse
Authors: Bing Xue and Jia-Liang Le

A SIMPLE METHOD OF ENHANCING THE ROBUSTNESS OF R/C FRAME STRUCTURES

By: Yihai Bao, H.S. Lew, Fahim Sadek, and Joseph A. Main

Synopsis: A simple debonding technique was proposed to reduce strain localization in reinforcing bars in the region of wide flexural cracks in reinforced concrete (R/C) beams, in order to enhance the resistance of R/C buildings to disproportionate collapse. Debonding was achieved by heat-shrinking polyolefin tube over the reinforcing bar. Results from testing of a No. 8 reinforcing bar showed that with an 8 in (203 mm) debonding length on both sides of a ¼ in (6.35 mm) wide gap, simulating a wide flexural crack, the elongation of the reinforcing bar prior to fracture was about 38 % more than for the case without the debonding technique. This observation demonstrated that the debonding method could effectively reduce strain localization, thereby delaying the fracture of reinforcing bars. To analyze the effects of debonding, detailed finite-element models of the test specimens were developed, which adequately captured the experimental results. R/C frame structures were analyzed by applying the debonding model under a column removal scenario. The results indicated that the debonding method could enhance the development of catenary action in the beams of R/C frame structures.

Keywords: disproportionate collapse, reinforced concrete, debonding, catenary action, nonlinear finite element analysis

Biography: Yihai Bao is an IPA researcher at the Engineering Laboratory (EL), the National Institute of Standards and Technology (NIST) and a project scientist at the Department of Civil and Environmental Engineering, the University of California - Davis. He received his BS and MS degrees from Tongji University of China and PhD from the University of California - Davis, Davis, CA. His research interests include nonlinear modeling of structural behavior under extreme loading conditions, large-scale experimental methods and advanced scientific computational methods.

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Joseph A. Main is a Research Structural Engineer at the Engineering Laboratory (EL), the National Institute of Standards and Technology (NIST). He received his PhD from Johns Hopkins University. His research interests relate to the computational analysis of structural performance under extreme loads, wind, fire, and disproportionate collapse.

INTRODUCTION

Recent experimental studies[1-4] on reinforced concrete (R/C) frame structures under column removal scenarios have identified the failure mechanisms that occurred when they underwent large deflections. In the tests of two full-scale frame assemblies[1], it was noted that the beam-end rotations under monotonic loads were approximately 7 to 8 times as large as those based on seismic tests under cyclic loads. However, the rotational capacity can be further increased if more ductility is achieved in the reinforcing bars at critical locations, such as at beam ends near column faces. The ductility of reinforcing bars is adversely affected by strain localization, which may occur at a wide flexural crack at a critical beam section, such as the one shown in **Fig. 1**. The exposed bar segment at the crack developed larger plastic strain than the embedded portions adjacent to the crack, due to the bond of surrounding concrete to the reinforcing bar. Premature fracture of reinforcing bars limits the further development of catenary forces in the beams.

The existence of strain localization was observed in the numerical analysis of two reinforced concrete frame assemblies, where the numerical models have been validated against experimental results[5]. **Fig. 2** shows the calculated plastic strain distribution of the beam bottom reinforcing bar near the unsupported center column just before the fracture. A steep strain increase in the bottom reinforcing bar was observed at the beam section near the unsupported column, where a wide flexural crack occurred during the test. To relieve the strain localization, a debonding concept is applied and illustrated in **Fig 3**. By debonding the reinforcing bar from the surrounding concrete at the potential crack zone, a more uniform strain distribution can be achieved, reducing the strain localization. To demonstrate the effectiveness of this concept, a detailed finite element model was created for one of the above-mentioned frame assemblies. The numerical model considered the debonding of the beam-bottom reinforcing bars near both sides of the unsupported center column with the debonding length equal to the beam depth. The plastic strain distribution of the bottom reinforcing bar is plotted in **Fig. 2**. A relatively uniform distribution was observed as a result of detaching the reinforcing bar from the surrounding concrete. The reduction of strain localization delayed the bar fracture, which resulted in a 14 % increase in the ultimate vertical load capacity and a 10 % increase in the corresponding vertical deflection of the center column as presented subsequently in Table 1 and **Fig. 14(a)**. Larger increases in capacity and deflection at failure were achieved with a larger length of debonding.

A simple approach is proposed herein to accomplish debonding between reinforcing bars and concrete. The effectiveness of this method is demonstrated through an experimental study. The experimental data are also compared with computational models, which are later used to investigate the influence of debonding length and evaluate the behavior of frame structures under seismic loads.