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A_s	Area of the reinforcing steel;
a	Element length;
$a(t)$	acceleration at time t
b	Element height, or beam width;
(C)	The damping matrix;
d	The distance between each spring, the diameter of the circle that fits into the element, or beam depth;
D	Dead load including façade loads
E	Young's modules;
E_c	Young's modulus of concrete;
E_s	Young's modulus of steel;
E_{sp}	The post-yield stiffness;
E_t	The post-yield tangent modulus;
E_y	The initial elastic stiffness;
{f}	The applied load vector;
F_i^*	The modified load vector value of degree of freedom "*i*";
F_{ult}	The ultimate stress capacity of the material;
F_{cu}	Concrete compressive strength;
f_y	Steel yield stress;
G	Shear modules;
G_{LD}	Increased gravity loads for Linear Static analysis
h	Beam total depth;
K	stiffness
(K)	The stiffness matrix;
L	Live load
(M)	Mass matrix;
m	mass
Q_i	Load effect
(R)	Transformation matrix;

R_n	Nominal strength
S	Snow load
$s(t)$	displacement at time t
S_L	geometric scale factor
T	Element thickness;
t	Time in second
v_0	initial velocity
U_u	total bond force
[X]	The displacement vector;
Δ_j	The assumed displacement of degree of freedom number "j";
$\Delta f(t)$	The incremental applied load vector;
δ_o	The yield displacement;
ε_{ult}	The ultimate strain capacity of the material;
$\varepsilon_{\boldsymbol{u}}$	The ultimate strain of the concrete;
ω	The natural circular frequency of a structure;
ω_1	The first natural frequency;
ζ	The damping ratio;
Φ	Strength reduction factor
θ_{pra}	plastic rotation angle
θ_y	yield rotation angle
Ω_{LD}	Load increase factor used for linear static analysis
μ	Poisson’s ratio
σ	stress
ρ	density of concrete

ABSTRACT

The progressive collapse of buildings is initiated when one or more vertical load carrying members (typically columns) is removed or collapsed. After losing of the original load path due to column removal, the load may be transferred to an alternate path. For flat slab buildings, when a supporting column is instantaneously removed, the likelihood of disproportionate collapse depends on the strength and deformation capacity of the neighboring slab column connections as well as the forces and deformations demands caused by the dynamic loading effects.

Numerous tests have been conducted on isolated slab-column connections with lack of in-plane restraints and dynamic load applied to the specimens. The Non-existence of these tested specimens in an actual flat-slab system makes tests data questionable to be used for accurately defining of the strength and stiffness properties of slab-column connections. Additionally, only a few flat-slab specimens with multiple slab panels have been tested and static rather than dynamic loading was applied to these specimens. The combination of lack of knowledge about the dynamic disproportionate collapse performance and extensive use of flat-plate structures makes this research important to be carried out to protect the occupants of flat-plate buildings. The research presented herein is motivated by the existing gap in knowledge regarding to the vulnerability of the associated risk of progressive collapse in flat plate structures.

The research proposed herein seeks to fill in the gap in existing knowledge for the dynamic disproportionate collapse potential of the flat slab buildings by providing analytical and experimental modeling approaches. To achieve this objective, a three dimensional, ¼-scale flat slab model building was constructed for progressive collapse testing. The flat-slab model was tested by subjecting it to a sudden loss of its supporting columns. Three columns were completely removed from the structural model one each time. As each column was removed, the reinforcement strains, displacements and accelerations were measured to be analyzed and compared with the analytical results extracted from analysis using the Applied Element Method. By adopting agreement between the analytical and experimental results, a numerical study for the effects of the design parameters considered in assessing the progressive collapse potential of flat slab structures was conducted. The analytical results showed that, flat slab structure systems have greater vulnerability to progressive collapse compared to beam-column-slab structures. The analytical results also showed that, the increase of column size enhance flat slab building resistance to progressive collapse and that, the modification of continuity of flat slab model by only 0.25m cantilever indicate significant effects on the flat slab structure resistance to progressive collapse.

Chapter 1 : Introduction

1.1 Background

The topic of progressive collapse has taken the attention of many researchers in recent years due to many structural collapse associated with accidents or terrorist attacks or failure of structural elements. The progressive collapse of buildings is initiated when one or more vertical load carrying members (typically columns) is removed or collapsed. After losing the original load path due to column removal, the load may be transfer to an alternate path. The loads from the upper floors will be redistributed quickly within a few milliseconds. As a result, all floors above the first floor will deflect identically and dynamically under uniform gravity loads to seek a new equilibrium path. The building will not collapse immediately due to spatial action of structure and catenary action of the frame beams or slabs.

The term of progressive collapse has been used to describe the propagate of an initial local failure in a style like a chain reaction that causes to partial or total collapse of the structure. The basic characteristic of the progressive collapse that the end state of the destructions is disproportionately greater than the failure that initiate the collapse. The design guidelines (ASCE 7-10, DoD 2009, ACI 318-11) guarding against disproportionate collapse are based mainly on engineering experience as well as limited numerical and experimental studies. The research proposed herein seeks to fill in the gap in existing knowledge for the dynamic disproportionate collapse potential of flat-slab structures by providing experimental and numerical modeling approaches.

1.2 Historical events of building progressive collapse

In this section, attempt has made to provide brief information on some of the significant structural failures in past which have presented the worldwide opportunities to evaluate the validity of engineering approaches and design procedures. The research regarding progressive collapse was initiated by the well-known collapse of Ronan Point apartment tower on May 16, 1968 as shown in Figure 1.1, due to an internal gas explosion at the 18th floor, which knocked out load bearing precast concrete panels near one corner of the building [30].

Another recent event takes the attention of civil engineers in 1995 after the collapse of the Alfred P. Murrah federal building in Oklahoma, USA. A bomb explosion occurred at the ground level next to the nine-story reinforced concrete office building. The side facing the blast had corner columns and four other perimeter columns. The blast shock wave disintegrated one of the 0.50 × 0.92 meter perimeter columns and caused brittle failures of two others [9]. The transfer girder at the third level above these columns failed, and the upper-story floors collapsed in a progressive fashion. Approximately 70 percent of the building experienced dramatic collapse. One hundred sixty-eight people died, many of them as a direct result of progressive collapse. Damage might have been less if this structure not relied on transfer girders for support of upper floors, if there had been better detailing for ductility and greater redundancy [Figure 1.2].