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Next Generation Damage and Post-Crisis Needs Assessment Tool for Reconstruction and Recovery Planning

Capability Project

The Structural Assessment Module

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ABBREVIATIONS AND ACRONYMS

ABBREVIATION	DESCRIPTION
$A_{si}(cm^2/m)$:	Area of cross section of rebars
$A_{c0}(cm^2/m)$:	Area of concrete finite element
γ_G :	Safety factor for permanent loads
γ_Q :	Safety factor for live loads
$\Delta\delta_i$:	Differential settlement
D :	Damage Ratio
ε_c :	Strain of concrete
ε_o :	Axial strain
ε_{cD} :	The starting strain of the unloading branch (end strain of the previous loading branch)
ε_{cR} :	The end strain of the unloading branch for $\sigma_c = 0$
ε_{cs} :	Shrinkage coefficient of concrete
ε_{cu} :	Ultimate strain of concrete in compression
ε_{cy} :	Yield strain of concrete in compression
ε_{si} :	Strain of the rebar i
ε_{sn} :	The limit steel strain of the loading branch n
ε_{su} :	Ultimate strain of steel
ε_{sy} :	Yield strain of steel
E_{co} :	Tangential modulus of elasticity of concrete in compression for $\sigma_c = 0$
E_s :	Modulus of Elasticity of steel
ζ_n :	Coefficient of load variation at time n
f_{cy} :	Yield strength of concrete in compression
f_{sy} :	Yield strength of steel
h :	Height
κ_x, κ_y :	Curvatures
k_c :	Thermal conductivity of concrete
k_f :	Creep coefficient of concrete
$\lambda = \varepsilon_c / \varepsilon_{cy}$	Coefficient of thermal insulation
l :	*Length*
M :	Bending moment with respect to the center of gravity of the cross-section
M_R :	Bending moment of Resistance
N :	Axial force
N_R :	Axial force of Resistance
R_d :	Design resistances

S_d :	Design values of internal forces
S :	Spacing of stirrups
σ_{cD} :	The stress starting of the unloading branch for ε_{cD}
σ_{si} :	Stress of rebars i
σ_z :	tensile strength of cement paste
$t\ (days)$:	Age of the concrete
$t_o\ (days)$:	Age at which load is applied (Removal of formwork)
$t_s\ (days)$:	Starting time of drying
T :	Temperature
φ :	Creep coefficient
x_i, y_i, z_i :	Coordinates

EXECUTIVE SUMMARY

A structural assessment module, based on monitoring data from strain, acceleration, displacement and temperature sensors installed in reinforced concrete building structures, in combination with the use of a commercially available non-linear structural analysis software is developed, resulting to the near real time estimation of the structural condition for the structural members as well as the stability of the whole structure due to the following events.

1. Normal operating conditions
2. Earthquake
3. Explosion
4. Fire

The module consists of the following parts:

Part 1

Long term estimation of the variation with time of the actual loads applied on the structure and the resulting structural response. The module will receive in specific time intervals the inputs from the strain sensors installed on three reinforcing bars at corners of the bottom cross sections of the columns in the ground floor and will calculate the axial forces and bending moments developed. Furthermore it will calculate possible differential settlements and the percentage of the design live loads applied at the time of the measurement. By using a commercially available non-linear structural analysis program it will estimate the safety factors at critical cross sections of the structural members corresponding to the calculated loads and differential settlements.

Part 2

Short term estimation of the structural integrity due to the oscillations stimulated from earthquake. As a first step, the sequences of horizontal displacements at two extreme points of the floors and the foundation will be calculated after double integration of the inputs from the accelerometers. As a second step, these displacements will be introduced as imposed displacements to the commercially available non-linear analysis program on the structural model of the building. From the results of the analysis will be estimated (a) the local damage index at the critical cross sections of the structural members based on an energy based damage criterion, and (b) the overall instability index of the whole structure.

Part 3

Short term estimation of the structural integrity due to the oscillations stimulated from the blast after explosion. The reduced resistance of members heavily damaged from the blast is introduced in the structural model and the analysis is executed as in the part 2.

Part 4

Thermal effects on the strength of the structural members. A fire usually follows a blast implying the development of high temperatures varying with the position in the building and with time. The module will receive the inputs from the temperature sensors distributed over the whole structure. The temperatures at the position of the critical cross sections of the structural members and their variation with time will result from a space interpolation module. The rate of the heat quantity transferred to the structural members from the fire following the blast will be estimated and so will the reduced strength of concrete, steel and the critical cross sections. For this purpose the values of thermal conductivity, specific heat and thickness of concrete covering the reinforcing steel bars will be added to the properties of structural materials. The module calculating the internal forces will be modified by the introduction of the respective laws of variation of strength and deformability properties for the different finite

elements constituting the mesh over the area of each cross section with respect to their depth from the free surface of the member.

Part 1 is needed to provide input to the other Parts (on earthquake, explosion, and fire) on the structural condition at the time of the disaster. Part 1 depends on strain sensors embedded during the erection. In existing buildings where the installation of strain sensors is not possible, Part 1 can be eliminated and the structural assessment for the normal operating loads can result from the analysis of the structure for the known values of the dead and the quasi-permanent loads and the estimated value of the actual live load during the normal operation. This will still permit the evaluation of earthquake or fire structural response in existing buildings (accelerometers and temperature sensors do not need to be embedded and can be easily installed in existing buildings). This assessment can be used to direct structural engineers to locations of physical damage, even if they are concealed behind architectural finishes. Moreover, this assessment has been used with construction cost-estimation principles to estimate repair cost which is invaluable for quickly arranging for financing. The parts 1 and 2 consist of the software prepared for the MEMSCON project (www.memscon.com)[1] properly refined to accommodate data and procedures destined to the incorporation of the parts 2 and 3 in the single module. The following innovations are introduced in the treatment of the structural assessment procedure.

- The analytic formulas for the constitutive law of the concrete are extended to contain expressions for the unloading and reloading branches which are developed during the cyclic repeated loading.
- Similar extension of the analytic formulas for the constitutive law of the reinforcing steel is introduced for the case of the cyclic repeated loading.
- A reconstruction procedure of the hysteresis loops pattern at the plastic hinges developed during a cyclic repeated loading due to earthquake or explosion.
- A calculation procedure for the estimation of the damage index at the plastic hinges is introduced based on the dissipated energy which is estimated from the corresponding hysteresis loops pattern. This constitutes the justification of the experimental manifestation of the generally accepted Parc-Ang[2] damage criterion.
- Analytical formulas for the estimation of the remaining stiffness of structural members heavily damaged and deformed after blast occurring at their vicinity.
- Analytical formulas for the experimentally detected effect of temperature on the strength and deformability properties of the structural materials.

[1] See References [13]
[2] See References [29]