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A coupled connector element for nonlinear static pushover analysis of precast concrete diaphragms

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ABSTRACT

This paper describes the formulation of a diaphragm connector element developed for use in two-dimensional finite element (2D-FE) modeling of precast concrete diaphragms. The connector elements, composed of assemblages of standard element types readily available in most FE software package libraries, are nonlinear, coupled for shear–tension interaction, enable friction mechanisms, and possess descending branch behavior. Element construction is based on data from full-scale tests of common precast diaphragm connectors. The 2D-FE models have been employed in nonlinear static "pushover" analysis of isolated floor diaphragms to determine diaphragm stiffness, strength, deformation capacity, and limit state sequence. The use of discrete elements to model the precast diaphragm connectors permits the direct evaluation of local force and deformation demands acting on these details. Further, the coupled formulation is adaptable to complex force histories and deformation patterns in the floor diaphragm, thereby permitting the element to respond in realistic fashion. The models, verified for accuracy using large scale testing, are providing crucial information on capacity and limit states for calibrating performance-based design factors for a new seismic design methodology for precast concrete diaphragms.

1. Introduction

Floor diaphragms are often treated as rigid and sufficiently strong in the analysis and design of building structures under seismic excitation. This assumption cannot always be made for precast concrete construction in which the floor system is composed of series of individual precast floor units. A critical feature of these diaphragms is the nature of the force transfer across the joints between the floor units. The units are joined by connectors alone or in concert with a thin reinforced topping slab. Thus, unlike the distributed force transfer in monolithic floor slabs that serve as diaphragms in reinforced concrete structures for instance [1], forces in precast diaphragms are transferred at the discrete connector locations. The floor joints serve as critical sections in the precast diaphragm, and thus precast diaphragm behavior is highly dependent on the characteristics of the connectors [2], including impacting the diaphragm global properties [3] and local failure modes [4,5].

Since the collapse of several precast concrete structures due to failures of the floor systems in the 1994 Northridge earthquake [6], steady progress has been made on understanding the behavior of precast floor diaphragms for the purposes of improving their seismic design. These advances in knowledge have been driven largely through analytical and experimental research, culminating in a project [7] developing a new precast diaphragm seismic design methodology [8], currently in the codification process [9,10].

Diaphragm analytical models used in research, like those used in the design practice, originally involved monolithic models, including Bernoulli beam formulations [11], fiber element and smeared crack models [12], and elastic plane stress finite elements [13–15]. However, recognizing the limitations associated with modeling precast diaphragms using monolithic models, precast diaphragm finite element (FE) models with discrete representations of the connectors have been developed. Early versions of these "discrete" diaphragm models included those capturing diaphragm flexure response only [12], and later flexure and shear response as uncoupled degrees of freedom (DOF) [4,16].

For the current research [7], the discrete diaphragm models are being used in extensive parameter studies to calibrate design

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Nomenclature

A	area of the link element
C_u	concrete peak compression force within effective area
E	concrete elastic modulus
f'_c	concrete cylinder compressive strength
k, k_{2L}, k_{3L}	initial, secondary, softening stiffness of link
$k_{1,2}$	stiffness in the link element
k_2^{ts}, k_2^{vs}	secondary tension, shear stiffness of uncoupled spring
k_c	contact stiffness
K_{ic}, K_{uc}	theoretical initial, secant compression stiffness of concrete
k_i^{cs}, k_u^{cs}	initial, secant stiffness of compression spring
k_i^{ts}, k_i^{vs}	initial tension, shear stiffness of uncoupled spring
L	length of the link element
$n_{1,2}$	force in one of link element
n_y	yield strength of link element
T	tension force
T_Y	connector tension yield strength
t	thickness of the plane stress element
t_y	tension yield strength of uncoupled spring
V	shear force
V_Y	connector shear yield strength
V_Y^C	connector shear yield strength under compression
v_y	shear yield strength of uncoupled spring
Δ_T, Δ_V	tension, shear deformation
Δ_{TOT}	Total deformation
Δ_{TY}, Δ_{VY}	tension, shear yielding deformation
Δ_{TYf}, Δ_{TYs}	tension full, soften yielding deformation
$\Delta_{uT,red}$, $\Delta_{uV,red}$	reduced ultimate tension, shear deformation
Δ_{VYf}, Δ_{VYs}	shear full, soften yielding deformation
κ_t, κ_v	tension, shear soften stiffness ratio
Δ_{uT}, Δ_{uV}	connector ultimate tension, shear deformation
$\delta_{1,2}$	deformation in one of link
δ_u	ultimate deformation of link
δ_{ut}, δ_{uv}	ultimate tension, shear deformation of uncoupled spring
μ	full yielding-to-soften yielding ductility ratio
μ_s	coefficient of friction for contact element
θ	orientation angle of line element

factors for the new diaphragm design methodology [8]. For this work, a general "connector element" that can respond accurately to complex force histories in realistic fashion is a key feature of the discrete diaphragm model. This paper describes the formulation of such a connector element for two-dimensional finite element (2D-FE) representations of the precast concrete floor system. The elements are nonlinear, coupled for shear and tension interaction, enable friction mechanisms, and possess descending branch behavior. The connector elements are composed of assemblages of standard elements readily available in most FE software package libraries, and are feasible for large DOF models.

The formulation is derived generically in this paper. Element construction is then demonstrated for a number of common precast diaphragm connectors. The element construction depends on data from full-scale tests performed on an assortment of common precast connectors [17,18], tested as part of the overall research effort [7], and supplemented with data from existing tests of precast connectors [19–21]. The resulting element response is compared to physical tests and a comparable user-defined element.

The 2D-FE discrete models have been used extensively in the research project for nonlinear static analyses of isolated diaphragms under increasing monotonic in-plane inertial forces to determine the precast diaphragm stiffness and strength characteristics, deformation capacity, and limit states sequence [22]. Such analyses are similar to so-called "pushover" analysis [23] used to evaluate the capacity of the lateral force resisting system (LFRS) e.g. shear walls, moment frames, and this same terminology is adopted here. The importance of using the coupled element in the 2D-FE discrete model is demonstrated in pushover analyses for a number of common diaphragm layouts at the end of this paper.

Determining diaphragm capacity through pushover analyses is a key initial step in developing the performance-based seismic design methodology. A complementary step, determining anticipated diaphragm seismic demands, is accomplished via three-dimensional (3D) nonlinear dynamic time history analysis [24]. The extension of this connector element for use in the 3D-FE model, and the verification of these models using large scale testing of joints and structures is presented in [25–27] respectively.

2. Precast diaphragms

2.1. Precast diaphragm design

Diaphragms are reinforced to carry the in-plane shear, flexure and anchorage forces associated with seismic loading. This action is required in order to provide a complete load path for the inertial forces to reach the primary elements of the LFRS, i.e. shear walls or moment frames [1]. In precast structures, reinforcing of the diaphragm involves placing connectors between the precast floor units. Transfer is made solely by these connectors in an untopped diaphragm [28,29]. In a topped (composite) diaphragm, a thin cast-in-place topping also participates, but since the diaphragm cracks along the joints, the force transfer mechanism is similar.

Fig. 1(a) shows a simple diaphragm schematic with typical floor diaphragm dimensions and connector layouts, indicating the connectors intended to transfer: (b) in-plane shear force between the units; (c) chord forces associated with in-plane flexure; and (d) collector/anchorage forces to walls and frames. Typical diaphragm connector layouts and connector dimensions are shown in the figure.

2.2. Precast diaphragm connectors

Element construction for the 2D-FE connector models is demonstrated in this paper for a set of commonly-used flange-to-flange connectors [see Fig. 1(b)–(d)]: (b) a *JVI Vector*[1] for shear reinforcement; (c) a *dry chord connector* for flexure reinforcement; and (d) *angled bar-plate connectors*, often used one-sided [as shown in Fig. 1(d)] to connect precast floor units to beams and walls. It is noted that a wide variety of connectors are used in practice to provide precast diaphragm reinforcement, including standard industry hardware and proprietary connections [3]. These particular connectors are chosen as they: (1) have traditionally found widespread use; (2) have been extensively tested [17–21]; (3) together provide the complete set of reinforcement required for an untopped precast floor diaphragm; and, (4) transfer force similarly to most connections, i.e.

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[1] Proprietary precast flange-to-flange connector, JVI, Inc. Lincolnwood, IL 60712.