Session 1

Nonlinear Analysis on the Collapse of Daikai Station Subway Tunnel during the Hyogo-ken Nambu Earthquake of January 17th 1995

S. Takada*
M. Abdel-Aziz**

1. Introduction

The tunnel at Daikai Station of Kobe City Municipal Subway had collapsed as a result of the Hyogo-ken Nambu Earthquake of January 17th, 1995. A two-dimensional finite element computer program is developed in order to investigate the behavior of this tunnel during the earthquake. The program utilizes a new finite element reinforced concrete inelastic model which could take account of concrete cracking, concrete and/or steel yielding, concrete crushing, steel failure, as well as shear failure in concrete and in shear reinforcement. Other features such as soil plasticity, soil-structure interaction, vertical acceleration (as well as the horizontal one), dead load, dynamic earth pressure, and large displacement analysis are also considered in the program.

2. A New Reinforced Concrete Nonlinear Model

A new inelastic stiffness matrix for straight reinforced concrete elements is derived based on the "Plastic Hinge Idealization" and the "Basic Principles of Reinforced Concrete Structures". The material non-linearity is simplified to a bilinear model with strain-hardening. The criteria for various critical states of stress (strain) are as follows:

2.1 Concrete Cracking

A crack is developed if the tensile stress exceeds the allowable one of concrete. Two types of cracks are assumed. An elastic crack, which will close if the bending moment is reversed (on condition that yielding does not occur), and a plastic or permanent crack are developed by yielding (unless compression yielding occurs). If a crack occurs, the area and inertia of the virtual section is used to calculate the stiffness matrix.

2.2 Yield and Concrete Failure Interaction Surfaces

Yielding may take place in the extreme fibers of concrete if a 0.002 strain[1] is reached provided that steel bars had not yielded, or in steel bars if the yield stress is reached provided that concrete had not yielded. A balanced yielding occur if both concrete and steel bars yield at the same instant[1]. An approximate interaction surface is constructed for each section as shown in Fig.1. A plastic hinge is formed at an element end if the combination of the axial force and bending moment lie on or outside the yield interaction surface, and the stiffness matrix coefficients are modified. The approximate failure interaction surface shown in Fig.1 is constructed based on an ultimate concrete strain of 0.0035, an ultimate concrete stress of 0.85 that of the maximum, and an equivalent uniform stress distributed over a distance of 0.80 the neutral axis depth[1]. Concrete crushes at an element end if the combination of the axial force and bending moment lie on or outside the failure interaction surface. Once concrete failed in one section, its area and inertia are modified to be the area of steel reinforcement.

* Professor, Dept. of Architecture & Civil Engineering, Kobe University, Rokkodai, Nada, Japan.
**Graduate Student (Ph.D.), Graduate School of Science and Technology, Kobe University.

2.3 Concrete failure by Shear

Concrete also may fail by shear when its maximum shear strength is attained. It is assumed that shear reinforcement (stirrups, hoop ties and bent bars) yields at the same instant of concrete failure[1].

2.4 Reinforcement failure

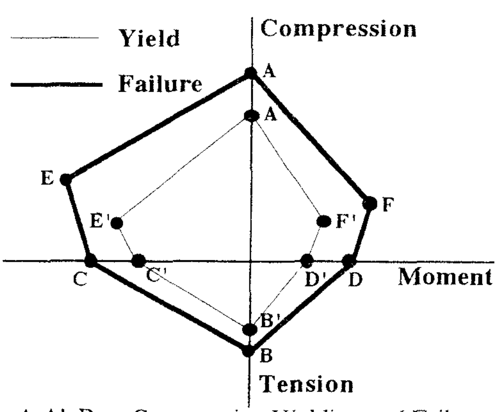
Failure of reinforcement will only take place after concrete fails either by cutting of tensile reinforcement (attained when its strain reach its ultimate value 0.35 equivalent to an ultimate stress of 3.482tf/cm^2) and/or buckling of compressed reinforcement.

2.5 Element Stiffness Matrix

It is possible that one end of an element cracks while the other end is still uncracked. Consequently, the two ends do not have the same area and inertia. An average for those values may not lead to accurate results, because the cracked sectional area and inertia is much less than the uncracked ones. An appropriate solution is to assume a linear change of area and inertia between the two ends. The integral expressions of the stiffness matrix of such element are solved using the computer program Mathematica.

3. Numerical Results

The tunnel is analyzed under the horizontal and vertical accelerograms recorded at Kobe Ocean Meteorological Observatory, whose peaks are -536.47cm/sec^2 at 6.94sec and 249.22cm/sec^2 at 4.50sec respectively, on the assumed base rock. The preliminary results show that the response increases rapidly after 3.86sec and the tunnel collapsed mainly due to shear failure in the middle column at 4.0sec. However, more refinements and modifications in the computer program are still under consideration. The time histories of the normal and shear forces in the middle column are shown in Fig.2.



A,A': Pure Compression Yielding and Failure
B,B': Pure Tension Yielding and Failure
C,C': Pure Bending Yielding and Failure
D,D': Pure Bending Yielding and Failure
E,E': Balanced Yielding and Failure
F,F': Balanced Yielding and Failure

Fig.1: Yield and concrete failure interaction surfaces

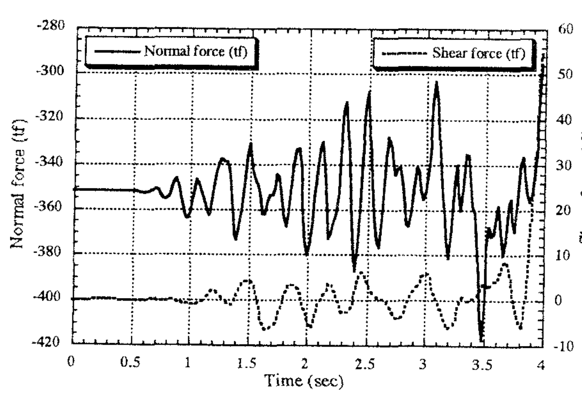


Fig.2 Normal and shear forces in middle column

Reference

1. "Japanese Standard Specification for Design and Construction of Concrete Structures", Part I (Design), 1986.