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CLEAVAGE SHEAR EXPLOSION OF REINFORCED CONCRETE SHORT COLUMNS BROKEN DOWN BUILDINGS AND THE HANSHIN-EXPRESS HIGHWAYS AT THE RECENT HANSHIN-AWAJI-EARTHQUAKE IN JAPAN ON THE 17. JAN. 1995

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ABSTRACT

Many reinforced concrete buildings and elevated highways as well as railways were broken down by the explosive cleavage shear failure of their reinforced concrete short columns, on which are already given warnings by the author since the year 1966 (Yamada <u>et al.</u>, 1966), at the recent Hanshin-Awaji-earthquake, Japan, 17. Jan. 1995 again. This report presents as some typical examples of this fracture mode, the Nishinomiya City High School and the Hanshin-Express-Highway will be discussed. Through the discussion it will be given again warning on the existences of such dangers throughout the world.

KEYWORDS

Shear explosion; reinforced concrete; short column; fracture; cleavage failure

SHEAR EXPLOSION OF REINFORCED CONCRETE SHORT COLUMNS

Explosive shear failure of reinforced concrete short columns was found at the first time by the author in the year 1966 (Yamada <u>et al.</u>, 1966) and given his warnings of the existing dangers of ordinary designed reinforced concrete buildings with short columns with a shorter shear span ratios a/d than 2 (or height to depth ratios H/D than 4). Photo 1 shows slightly before, at the instance, and after shear explosion.

This warning was proved by the fracture of many school buildings at the Tokachi-Oki-earthquake, Japan, 16. May 1968. This newly founded fracture mode was reported by the authors (Yamada <u>et al.</u>, 1968) and given warning on the existence of dangers in ordinary reinforced concrete buildings. The warning was verified again by the explosive shear fracture of reinforced concrete short columns in newly built school buildings at the Miyagiken-Oki-earthquake, Japan, 12. Jun. 1978.

<u>Explosive Cleavage Shear Failure</u>

Explosive cleavage shear failure of reinforced concrete columns occurres by the predominant shear force under the combined action of axial load, shear and bending. This condition may be realized at the shorter columns than the critical shear span ratios $(a/d)_{cr}$, about 2 (or $(H/D)_{cr}$, about 4). The longer columns with a shear span ratios larger than the critical shear span ratio $(a/d)_{cr}$, about 2 or $((H/D)_{cr}$, about 4 may yield under bending moment with sufficient ductility. Photo 2 shows the influences of the values of shear span ratios, axial load levels upon the fracture,

shortly before | at the instance | shortly after

Photo 1 Shear Explosion of reinforced concrete short column with a shear span ratio (a/d)=1,8 or (H/D)=3, under a constant axial losd level X=1/3, (Yamada, <u>et al</u>.(1968).

(a/d)=0,6	1,2	1,8	2,4	0,6	1,2	1,8	2,4
(H/D)= 1	2	3	4	1	2	3	4
$[X=\frac{1}{6}]$	Shear Explosion ←		→ Bending Yield	$[X=\frac{1}{3}]$	Shear Explosion ←		→ Bending Yield

Photo 2 Critical Shear Span Ratio between Shear Explosion and Bending Yield (Yamada, <u>et al</u>.(1968); Yamada,(1974))

especially the transion of fracture mode from shear explosion to bending yield.

Critical Shear Span Ratio $(a/d)_{cr}$ or $(H/D)_{cr}$

The value of the critical shear span ratio was given by the author (Yamada, 1974; Yamada et al., 1974) as a function of reinforcing index $\omega = (f_y/f'_{cu})\rho$ and axial load level ratio X (= N/N_0) as follows:

$$(a/d)_{cr} = \frac{4}{7}\,\frac{X + 2(1 + X)(f_y/f'_{cu})\rho}{\sqrt{-0{,}10X^2 + 0{,}09X + 0{,}01}} ,$$

where
- f_y, specific yield strength of longitudinal reinforcement of column,
- f'_{cu}, specific compressive strength of concrete,
- ρ, ratio of tensile reinforcement,
- ω, reinforcement index (= $(f_y/f'_{cu})\rho$),
- N, working axial load,
- N_0, yield axial load of centrally loaded column,
- X, axial load level ratio or ratio of working axial load N to yield axial load N_0 ($X = N/N_0$).

This value divides the two fracture modes of reinforced concrete column between explosive cleavage shear fracture of short column and bending yield of long column with sufficient ductility. Fig. 1. shows the critical shear span ratio as the function of axial load level ratio X and reinforcement index ω.

SHEAR EXPLOSION OF REINFORCED CONCRETE SHORT COLUMNS IN THE HANSHIN-EXPRESS-HIGHWAY

At the Hanshin-Awaji-earthquake, Japan, 17. Jan. 1995 many reinforced concrete short columns in the Hanshin-Express Highway No.3 between Osaka and Kobe, Japan, with round or rectangular cross section were broken down by the typical shear explosion (Yamada, 1996). Some examples are illustrated in Photo 3.

These columns were designed in the year 1966-1967 under the loading condition with a horizontal earthquake load level as 0,2 of gravity acceleration and simultaneously as vertical earthquake load level as 0,1 of gravity acceleration, which was the specially sivere design condition at that time. At that time, the warning of the author on the existence of the damages by the explosive cleavage shear failure of such reinforced concrete short columns was not popular and not recognized generally. It was verified later in the year 1968 by the Tokachi-Oki-earthqauke, Japan, and 10 years later by the Miyagiken-Oki-earthquake, Japan, 1978.

SHEAR EXPLOSION OF REINFORCED CONCRETE SHORT COLUMNS IN THE NISHINOMIYA-CITY HIGH SCHOOL

Many reinforced concrete buildings, which were designed by former old design codes with a lower earthquake loading assumption such as 0,2 of gravity accleration as horizontal earthqauke load level, were broken down by the explosive cleavage shear failure of their short columns. As a typical example of such collapse process of building by the shear explosion of reinforced concrete short columns are shown in the Nishinomiya City High School, which was designed in the year 1968 according to the old design code with a earthquake horizontal load level of 0,2 of the gravity acceleration.

Building

This 5 story building with 81 m x 11 m such as illustrated in Photo 4 was built upon a reclaimed pond and supported by prestressed concrete piles with a diameter of 35 cm. The piles under two bays of the east end of this building were driven into fairly stiff ground, which was former bank of the pond. On the contrary the piles under the main part of this building 14 bays of western side were driven through reclaimed soil with a thickness of about 3 m and into deeper and the level of this main part

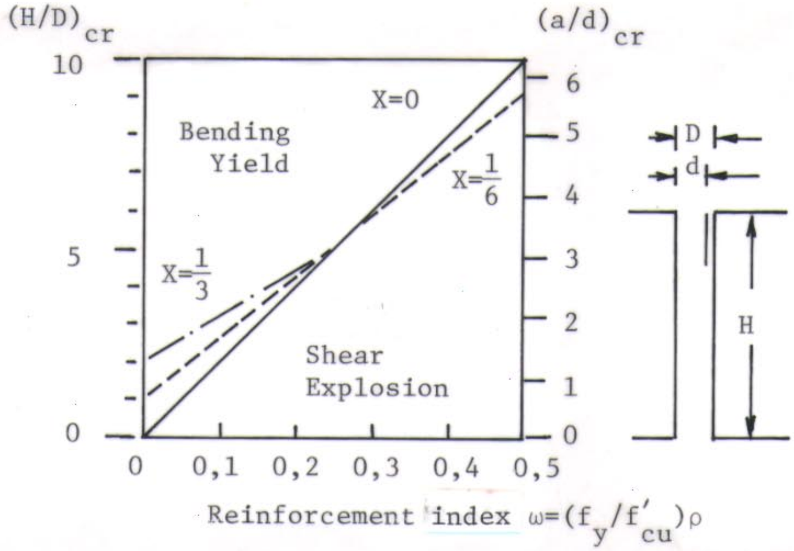


Fig. 1. Critical Shear Span Ratio $(H/D)_{cr}$ or $(a/d)_{cr}$
(Yamada,(1974); Yamada, <u>et al</u>.(1974))

(a) circular

(b) rectangular

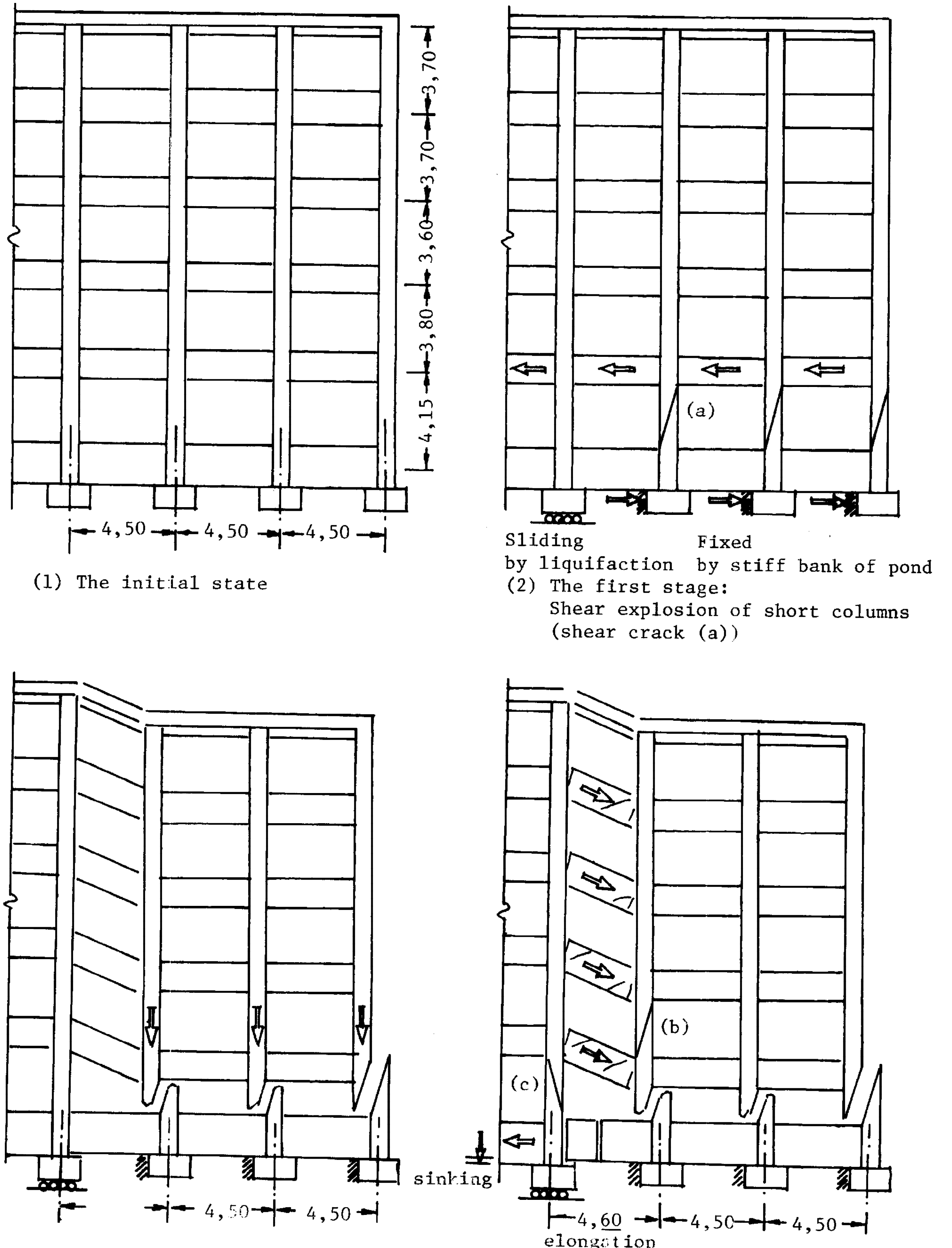
Photo 3 Destroyed reinforced concrete short columns in the Hanshin-Express Highway No.3 by typical Creavage Shear Explosion, at the Hanshin-Awaji-earthquake, 17. Jan. 1995,(Yamada,(1996)).

Photo 4 The Nishinomiya City High School

Photo 5 The east two bays

(a)

Photo 6 Detail of the third bay



(1) The initial state

(2) The first stage:
Shear explosion of short columns
(shear crack (a))

(3) The second stage:
falling down of the east two bays

(4) The third stage:
pullong down of the third bay at the east end (shear crack (c))

Fig. 2. Deduced collapse processes of the Nishinomiya City High School at the Hanshin-Awaji-earthquake, 17. Jan. 1995, (Yamada,(1996)).

are sunk down about 10 cm lower than the east two bays. The liquifaction traces between reclaimed soil and the bottom of the former pond are recognized at the boreing investigation by Professors Nishida, Yao et al., Kansai Univ., Osaka, Japan, on July-Aug., 1995.

At the west end of this building there is a small stream and the retaining wall at the west end of this building was pushed out westway about 1 meter.

Collapse State of this Buliding

The east two bays are completely broken down by the shear explosion of the columns in the 1st story like Photo. 5. The third bay from the east end was inclined down to eastway.

Deduced Collapse Process of this Building

From such collapse state of this building, the collapse process may be deduced by the author as follows:
At the first earthquake shock to the eastwards in the ground, the whole building was pushed to the westwards. The east two bays of the building were fixed at the stiff bank of the former pond. On the contrary, the main part of this building with 14 bays in the western side was sliding to the westwards by the liquifaction at the liquifacted layer under 3 m. Then the columns in the first and second story were sheard off, which remain after shock very clearly as shear creck pattern diagonaly from east upper to west lower. Especially the 6 columns in the first story in the two bays at the east end were sheard off instanteneously by the huge horizontal pulling force of main western building to westwards such as illustrated in Fig. 2.-(2) like the fracture process state (2) by the stiff fixing action of their basis. By the pulling of main western side building part to westwards, the third bay was streched out and the elongation of the span reachs over 10 cm at the base beam.

By the dead weight of the upper part of about 620 t of the two bays of east end, of which area is about 100 m^2, might fall down like the fracture state (3) in Fig. 2.-(3).

At the falling down process of the east two bays, the third bay might be pulled down at the east end. Then the neighbouring columns at the west end of this bay were pulled by east neighbouring beam to east downwards. It was formed shear cracks of opposite direction i.e. west upper to east lower such as illustrated in the fracture process state (4) and clearly recognized in the Photo. 6. (left hand side column).

Then gradually sinking down the main western part 14 bays of this building uniformly about 10 cm deeper than the eastern falling down part of 2 bays.

Deduced Excited Acceleration in this Building

Ultimate shear resistance of a column with a cross section of 70 cm x 40 cm may be estimated 700 ~ 800 kN under the action of an axial compression of about 1000 kN at the 1st story (without axial load may be 500 ~ 600 kN), (Yamada, 1974). The dead weight of the whole building may be estimated about 4500 t and the two and half bays of the east end may be estimated about 620 t. Therefore, the exicated earthquake acceleration in this building at the first story at the first shock may be deduced as about 800 gal.

WARNING ON THE EXISTENCE OF THE DANGERS OF SUCH SHEAR EXPLOSION OF REINFORCED CONCRETE SHORT COLUMNS

The author would like to give again and again his warning on the existence of the dangers of complete collapse of reinforced concrete buildings with short columns by their very dangerous explosive cleavage shear fracture without ductility!
The existence of this danger was proved again at the Hanshin-Awaji-earthquake.

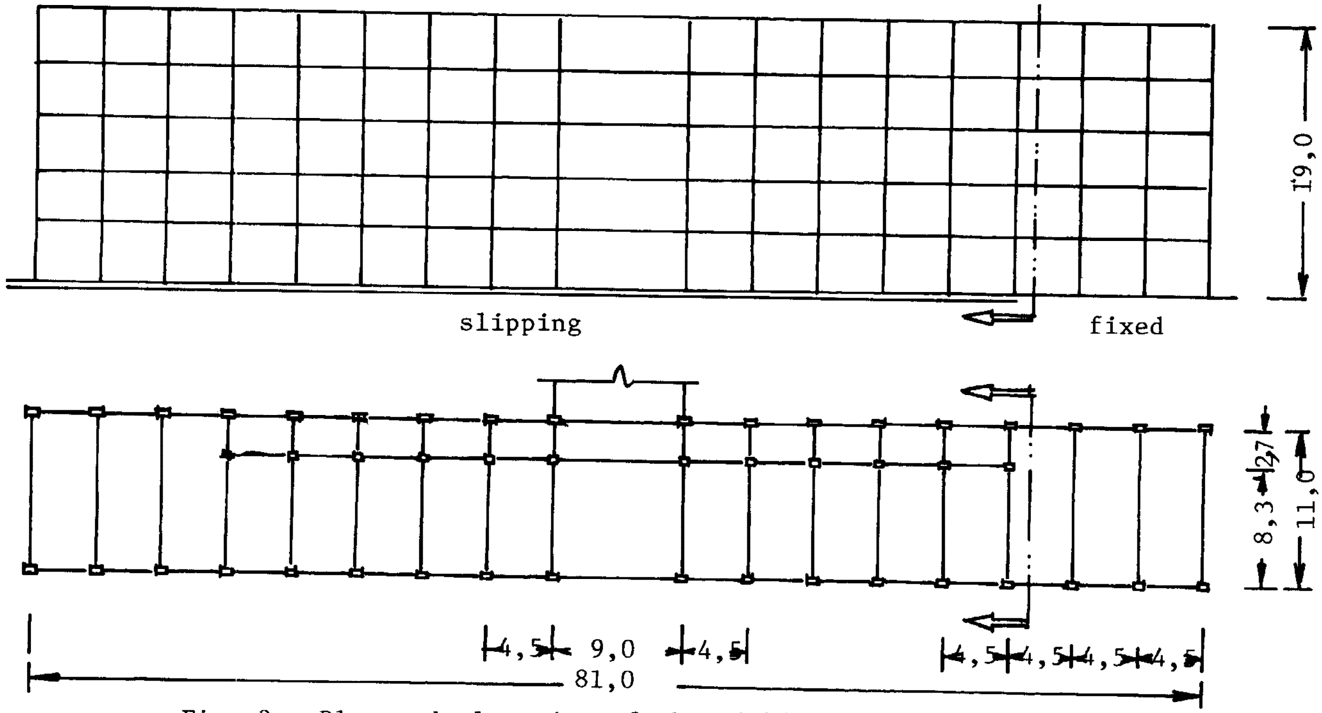


Fig. 3. Plan and elevation of the Nishinomiya City High School

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