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DEVELOPMENT OF HIGH STRENGTH MILD STEEL DEFORMED BARS FOR HIGH PERFORMANCE REINFORCED CONCRETE STRUCTURAL MEMBERS

MORITA SHIRO[1] and SHIOHARA HITOSHI[2]

[1] Department of Architecture, Faculty of Engineering, Kyoto University,
Yoshida-honmachi, Sakyo-ku, Kyoto 606, Japan

[2] School of Engineering, Division of Architecture, the University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

ABSTRACT

A five-year national project to develop an innovative technology necessary for construction of high-rise reinforced concrete building using high-strength materials in seismic region had been ended 1993. It aimed not only development of the total technology from raw material to design methodology of innovative reinforced concrete building but also refinement of existing technology. As a part of the project, high strength mild steel deformed bars were developed. The object of this paper is to briefly introduce proposed quality standard for high strength mild steel deformed bars and their material properties. Several research results relating with particular problems arising from adopting high strength rebar such as the effect of confinement, bond and so on, are also described.

KEYWORDS

high strength steel; deformed bar; standard; high strength concrete; mechanical coupler; hook anchorage; confined concrete; bond strength, anchorage strength.

INTRODUCTION

A Japanese five-year national project developing an innovative technology relating to construction of high-rise reinforced concrete building in seismic region using high-strength materials had ended in 1993 (Aoyama *et al.*, 1996). The project had been called by a code name "New RC," the scope of which is so wide including (1) research on high strength concrete and high strength reinforcing steel bar, (2) tests of members using high strength materials, (3) modeling of member stiffness and strength, as well as (4) refinement of earthquake resistant design concepts applicable to reinforced concrete buildings.

As a part of the whole project, high strength steel deformed bars were investigated. High-Strength Steel (HSS) task committee chaired by Prof. Morita was established in 1988. Researchers from academy, construction industry, and researchers from steel makers cooperated to establish new standards for new types of deformed bars. The object of this paper is to briefly introduce proposed quality standards for high strength steel deformed bars and their actual material properties. Several research results relating with some particular problems arising from adopting high strength rebars such as the effect of confinement, bond and so on, are also described. Due to the limit of a space, many research items and detailed research results of HSS task committee are not included in this paper. Some of them are available in other publications (Kaku *et al.*, 1992) or cited here.

BACKGROUND OF THE STUDY

Usage of high strength steel for longitudinal reinforcing bars is rewarded as reduction of necessary amount of steel and thus reduction of reinforcement congestion. Usage of high strength steel for lateral reinforcement makes it possible to compensate the deficiency of brittleness observed in high strength concrete. Thus the usage of high strength steel is a good solution to enlarge the scope of high strength concrete in reinforced concrete structures.

Although high strength steel had been on the market, they had scarcely been used in non prestressed reinforced concrete building construction industry in Japan. Several reasons were identified before the launch of the New RC project as follows.

- High strength steel in market, such as prestressing tendon has stress-strain relation without yield plateau nor plastic elongation ductility. This has been regarded to lead poor ductility to non-prestressed reinforced concrete members.
- High strength steel is not effective to enhance serviceability such as reduction of crack width or deflection.
- High strength steel may need more developing length or splice length to get superior performance for bond and anchorage and this may cause problem in traditional reinforcing detail.
- Scarce experimental verification of the performance of member with the use of high strength steel to establish the design method for such members are available.

MECHANICAL PROPERTIES OF HIGH STRENGTH STEEL

Use of high strength steel both as axial reinforcement and high strength steel and as lateral reinforcement were aimed at, although the latter had been used before the NewRC project had started. Table 1 summarizes the quality specifications for HSS proposed by the HSS committee.

Specifications

There are 5 categories of steel type. Fig. 1. Illustrates the required performance in terms of stress-strain relations. The surface deformation of the HSS bars was chosen so that it should conformed to the requirement for existing deformed bar standard defined in JIS (Japanese Industrial Standard).

HSS for axial reinforcement USD685 and USD980 are intended to be used as longitudinal bars. The applicable range of bar size is from D13 to D41. The specification of USD685 requires stress-strain relation to start strain hardening at larger strain than 1.4%, as shown in Table 1 and Fig. 1. For USD980 steel, there is no requirement for the strain at the commencement of strain hardening. Both of the steel should have relatively low yield ratio to avoid strain concentration at plastic hinge zone. Various manufacturing process of USD685 were possible which includes adding strengthening chemical elements to molten steel. It results in higher strength due to atomic size effect (solid melting of replacement) or crystallization effect. Both of higher yield stress and strain can be achieved by finer crystalline particles. Added aluminum, titanium or niobium during the steel manufacturing process, and by heating and hot roll, fine crystalline particles of austenite can be obtained. On the other hand, heat treatment of quenching and tempering can be employed to the ordinary medium carbon steel with addition of chemical elements effective for quenching. Commercially available PC steel manufacturing process was applied to produce USD980. First heat treatment of quenching and tempering, or cold work of 10 percent strength is applied to steel with addition of special elements effective for heat treatment or cold work . Then brewing is applied to secure required high strength and ductility.

HSS for transverse reinforcement USD785 and USD1275 steel are available with nominal diameter less than 13 mm. So it is typically used as lateral reinforcement. It is manufactured by addition of reinforcing elements and heat treatment at the time of hot roll, then tempered automatically by remaining heat. They are manufactured according to the current JIS G 3536 "PC steel wires and PC strands" or JIS G 3109 " PC steel bars."

Mechanical Property after exposure to High Temperature

Fig. 2. and Fig. 3 are the example of strength change of high strength steel after exposure to high temperature and during heating, respectively. It can be concluded that strength change is similar to, and pose no problem like, currently used SD345 steel up to 500 degrees Celsius, which is the highest temperature expected in case of fire.

High-Stress Fatigue

High-stress fatigue test, supposing cyclic earthquake or wind load, showed that for USD685, stress amplitude directly affected the fatigue strength. For stress amplitude of 0.98 and 0.93 times the specified yield strength, the cycle number to failure changed from 6,000 to 10,000. USD980 has higher yield ratio than USD685, and test stress was high. Hence it appeared that the cycle number to failure was sensitive to the shape of surface deformation. It would be necessary to carry out fatigue test assuming the actual design condition to which high strength steel is exposed.

Corrosion of Steel in contact with different metal

Metal on electrically base side contacting with other metal corrodes due to difference of ionization. The high strength steel sometimes contains a lot of special chemical elements and may be used in combination with ordinary reinforcing bar. So tests of durability by accelerated corrosion under severe environment were carried out. Test results revealed that corrosion resistance of HSS was similar to ordinary steel, and corrosion due to different metal touch tended to occur on the lower strength side, but its speed was 0.001 to 0.019 mm per year under pH 12 environment.

Mechanical Coupling Splice

The bad weldability of HSS USD685 due to added chemical elements and heat treatment necessitated developing mechanical splicing system. Rebar with screw type deformation and screw coupler splice are combined with injected mortar grouting preventing play. Currently available coupler shape, size, and grouting material were found to be sufficient for satisfactory splice performance.

BOND STRENGTH AND DESIGN

Anchorage of Beam Bar in Exterior Joint

The required anchorage length varies according to the required anchoring force and concrete strength. Usually high strength reinforcement require a longer anchorage lenth and little data were available for anchorage design of high strength materials. So series of pull out tests were carried out to estimate the anchorage strength of longitudinal reinforcement anchored in high strength concrete exterior beam-column-joints by 90 deg or 180 deg bend bars (Fujii *et al.*, 1991). Parameters associated with the anchorage strength includes (1) concrete strength, (2) bend radius, (3) side concrete cover, (4) spacing of beam bars, (5) bend position, (6) bend direction, (7) projected horizontal length of embedment, (8) lateral reinforcement, (9) beam bar diameter and so on. It is revealed that most of anchorage resistance is provided at the bend rather than the tail end or the straight part. The anchorage failure occurs as the bearing failure at the bend provided that bond capacity at the end-tail portion is sufficient. When the side concrete cover is small, the bearing failure is combined with the splitting failure of side concrete cover. When the straight lead length is small, the failure takes a forms of cone-type pull out failure of concrete.

Based on the test results, empirical equations to predict the required projected embedment length and thecapacity of hooked bar anchorage were developed and proposed for design use. The minimum requirements are shown below.

- the projected embedment length should not be less than 8 bar diameter.
- the bend should start from a position beyond the central axis of the member to which bars are anchored.
- the end-tail portion of a 180 degrees bend should be more than 4 bar diameter and 60 mm
- the end-tail portion of a 90 degrees bend should be more than 10 bar diameter

Table 2 shows the necessary projected embedment length developed as the consequence of above-mentioned proposal. Upper and lower numbers correspond to cases where lateral reinforcement effect is neglected or considered, respectively. Blank indicate the particular combination of materials where anchorage of normal practice is not appropriate, and special attentions as to cover concrete depth or lateral reinforcement is necessary. To avoid reinforcement congestion in exterior beam column joint, mechanical anchorage using steel end plate was also investigated by tests (Murakami *et al.*, 1996)

Anchorage of Beam Bar

To obtain the strength of anchorage of straight beam bars passing through an interior column, pull out tests were carried out (Morita *et al.*, 1992). The parameters of the test included column size and beam diameters.

It was observed that beam bar slip in the join is small if the column section is sufficiently large and hence the hysteresis of members connected to the joint is stable with a large hysteresis area. In this case the shear resistance of the joint is provided partly bye the truss mechanism, thus the shear strength is also enhanced. On the other hand, if the column section is insufficient, the beam bar slip at the joint and the pull-out displacement at the column face increase, and hence the hysteresis of members shows inverted S shape with a small hysteretic area. Insufficient beam-bar anchorage also results in reduced compression bar effect, and the shear resistance of joint depends on the arch, or strut, mechanism only.

An equation to determine the suggested minimum ratio of column depth to beam bar diameter was proposed as a function of concrete strength, beam bar yield strength and others. Table 3 shows the calculated column depth, where the upper and lower numbers correspond to the column compression stress of one-sixth and one-third the concrete strength, respectively. The table is based on the assumption that tension and compression yield would take place at both faces of the column, and the column width per beam bar is greater than six times the bar diameter. It should be noted that the use of HSS inevitably involve a longer embedment length and larger column size, and the combined use of high strength concrete only partly compensates because the tensile strength does not increase in proportion to the compressive strength of concrete.

Buckling of Compression Bars

A limited number of concentric compressive tests of square columns lead to the following conclusions as to buckling of compression bars.

- Even the largest tie spacing of 8 bar diameter in the test was sufficient to produce compression yielding before buckling took place. Hence the maximum load was always dictated by the yield stress of axial reinforcement.
- The displacement at the maximum load increases to 1.2 or 2.2 times by reducing tie spacing to 6 or 4 bar diameter. Respectively. Tie spacing of 8 bar diameter is not sufficient to secure the deformation capability.
- the buckling cannot be prevented by increasing tie bar strength, but higher strength prevents a rapid decrease of compression capacity after buckling.

Based on these experimental findings, a set of design recommendations were developed. The minimum tie spacing of 6 bar diameter is recommended for HSS.

Lateral confinement

High-strength concrete inherently show brittle behavior after the maximum compressive strength reached. Lateral confinement using HSS confining bars should modify high strength concrete. Figures 4 and 5 show some typical stub column specimens tested . Specimens with larger size were also tested. Fig. 6 shows results of a series of test (Sakino *et al.*, 1994; Sun *et al.,* 1993a, 1993b) where lateral reinforcement ratio ρ_h is taken as a parameter. With the increase of ρ_h , a modest increase of the maximum strength and a conspicuous improvement of ductility can be seen. The effect of HSS lateral reinforcement may have a limit. As to straight bars of square hoops and interior ties, yielding may not be observed at the maximum compressive strength. Hence the yield stress in the equation to calculate confined strength should be limited to, say, 700 Mpa. As to circular lateral reinforcement, on the other hand, yielding was always observed in the tests, and the calculated confined strength using yield stress of lateral reinforcement did not necessarily overshoot. Hence yield stress up to 1,130 Mpa, which is the upper limit in the test, may be utilized.

Formulation of constitutive equation for FEM

Non-linear finite element method (FEM) became a popular and useful analytical tool for research to fill up gaps between experimental data. In the New RC project, a prevalent use of FEM was attempted (Noguchi 1993a, Noguchi 1993b, Noguchi 1994 Kashiwazaki 1994). As a guideline for FEM users in the project, the standard formulation of constitutive equations for high strength concrete and HSS, including confined concrete, was attempted. Several series of tests were carried out, specifically aiming at the development of constitutive equations. The guideline should be useful for many years to come for general use of non-linear FEM for reinforced concrete.

CONCLUDING REMARKS

Two types of high strength steel were identified and classified into five steel according to their strength and ductility. One type is with yield strength of 685 MPa or 980 MPa and they are multi purpose deformed bar for reinforced concrete member with high strength and high ductility considering required potential plastic deformation capability. The other type is with yield strength of 785 MPa or 1,275 MPa and they are for transverse reinforcement in particular for confinement or shear reinforcement with high strength and moderate ductility.

Deformed bars were produced by steel maker, through which, a) production process, b) adding material, c) fundamental mechanical properties, d) vulnerability of damage to cold bending, e) mechanical properties under high temperature, f) fatigue characteristics, g) feasibility of corrosion were examined. Couplers for splicing high strength rebars were also developed and the standard for evaluation of splice performance applicable to the bars was proposed.

The mechanical performance of hook anchorage embedded in high strength concrete were tested by pullout tests. Bond performance were tested by specially developed pull out tests and the required development length applicable to the combination of high strength steel and high strength concrete were proposed. The confining effect to high strength concrete using high strength confining steel bars were tested by compressive tests of stub columns and the equations to predict the strength increase due to confinement were extended for high strength material with respect to rectangular columns and circular columns.

These research results were incorporated into the final report which includes a standard specification for high strength concrete, standards for high strength steel and the design guideline of building using high strength materials.

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Table 1 Required Mechanical Properties of High-Strength Reinforcing Deformed Bars

Mechanical Properties	Type of Steel				
	USD685A[1)]	USD685B[1)]	USD980	USD785	USD1275
Tensile Yield Strength or 0.2% Offset Strength in Mpa (Y_P)	685-785	685-755	980 or larger	785 or larger	1,275 or larger
Maximum Tensile Strength in Mpa (T_S)	-----	----	-----	930 or larger	1420 or larger
Yield Ratio (Tensile Yield Strength) / (Maximum Tensile Strength) (Y_R)	less than 85%	less than 80%	less than 95%	-----	-----
Tensile Strain at the start of strain hardening in mm/mm [2)]	larger than 1.4%	larger than 1.4%	-----	-----	-----
Fracture Elongation in mm/mm measured within gauge length	larger than 10%	larger than 10%	larger than 7%	larger than 8%	larger than 7%
Applicable Minimum Inner Radius for 90 degree Bending[3)]	2 times of *d*		4 times of *d*	1.5 times of*d*	2.5 times of*d*
Limit of Application	for longitudinal reinforcement as well as transverse reinforcement			only for transverse reinforcements	

Note : 1. USD685 has two categories 'A' and 'B'
2. definition of this property is shown in Fig. 1
3. *d* : nominal diameter of deformed bar

Table 2 Required minimum projected development length for 90 deg standard hook

type of steel	concrete compressive strength (s_B) in MPa				
	35.3	41.2	58.8	78.4	98.0
SD345	11.5*d* 8.5*d*	10.0*d* 8.0*d*	8.0*d* 8.0*d*	8.0*d* 8.0*d*	8.0*d* 8.0*d*
SD390	15.5*d* 11.5*d*	13.5*d* 10.0*d*	10.5*d* 8.0*d*	8.0*d* 8.0*d*	8.0*d* 8.0*d*
SD490	---- ----	---- 14.5*d*	15.5*d* 11.5*d*	12.5*d* 9.0*d*	10.5*d* 8.0*d*
USD685	---- ----	---- ----	---- ----	---- 16.0*d*	---- 13.5*d*

where *d* : nominal diameter of the deformed bar

Table 3 Required minimum column depth for cross-shape beam-column-joint to assure good anchorage of beam bars which go through joint core

type of steel	concrete compressive strength (σ_B) in MPa				
	35.3	41.2	58.8	78.4	98.0
SD345	20.4*d* 17.9*d*	18.4*d* 8.0*d*	14.5*d* 12.8*d*	12.0*d* 10.5*d*	11.9*d* 10.4*d*
SD390	23.3*d* 20.4*d*	21.0*d* 18.4*d*	16.6*d* 14.5*d*	13.7*d* 12.0*d*	11.8*d* 10.4*d*
SD490	29.2*d* 25.5*d*	26.3*d* 23.0*d*	20.7*d* 18.2*d*	17.1*d* 15.0*d*	14.8*d* 12.9*d*
USD685	40.8*d* 35.7*d*	36.8*d* 32.2*d*	29.0*d* 25.4*d*	24.0*d* 21.0*d*	20.7*d* 18.1*d*

where, *d* : nominal diameter of the beam longitudinal bar

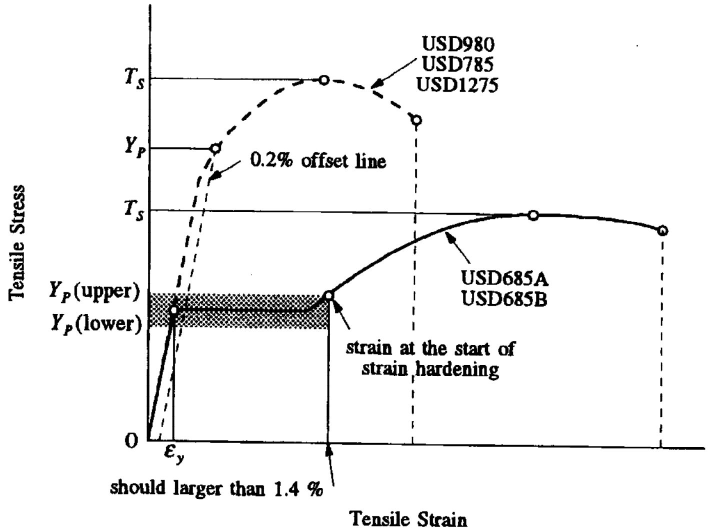


Fig. 1 : Demand for the Stress-Strain Relation of High-Strength Reinforcing Bar for NewRC Buildings

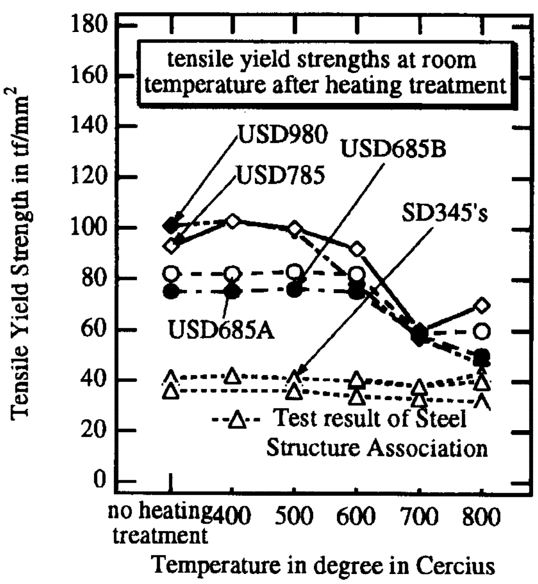


Fig. 2 : Tensile Yield Strength Degradation of High-Strength Reinforcements due to heating treatment

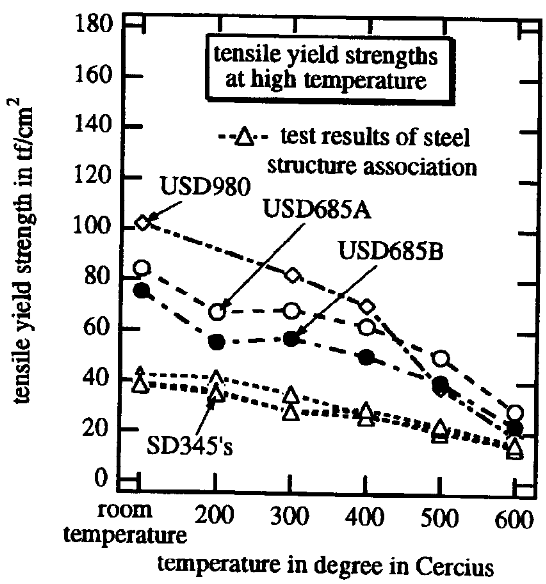
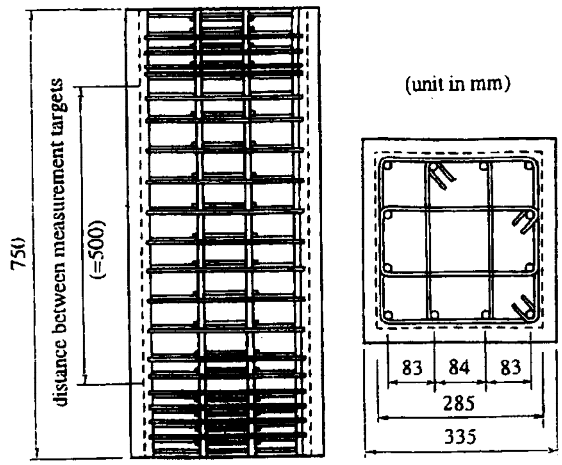
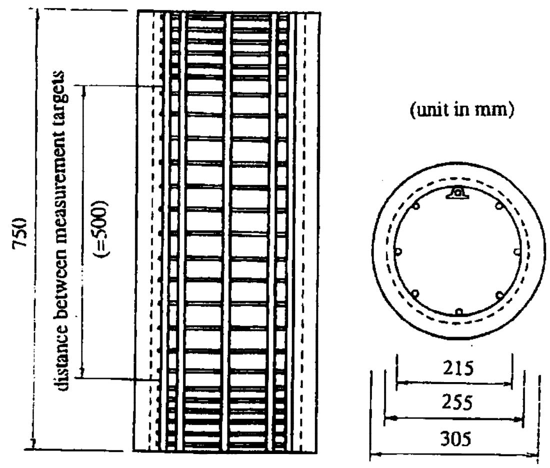


Fig. 3 : Tensile Yield Strength of High-Strength Reinforcement at high Temperature



some specimens did not have cover concrete (outside of the break line)

Fig. 4 : Reinforcing Detail of Square Column Specimens



some specimens did not have cover concrete (outside of the break line)

Fig. 5 : Reinforcing Details of Circular Short Column Specimens

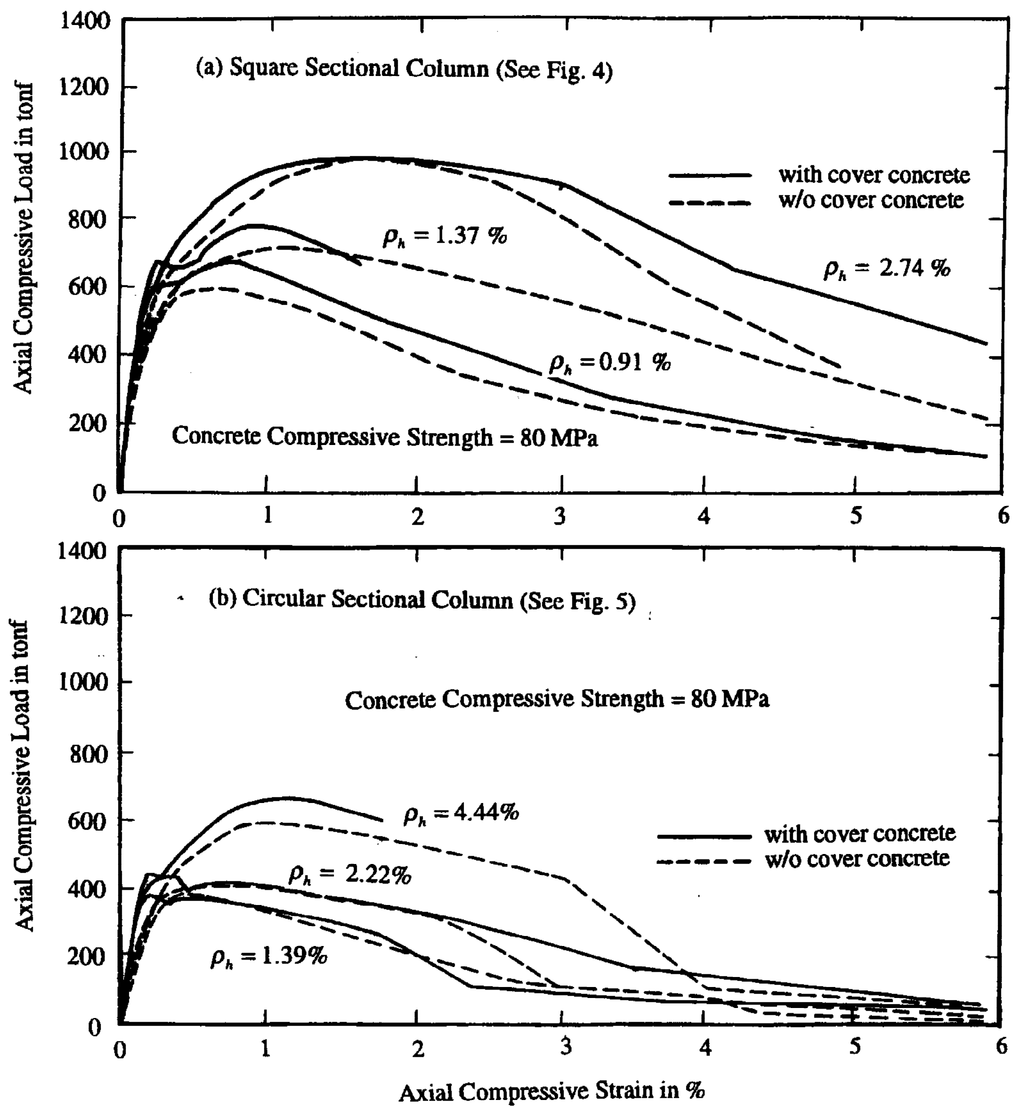


Fig. 9 Compressive Axial Load vs. Axial Strain Relation