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# Comparative Post-Yield Performance Evaluation of Flexural Members under Monotonic and Cyclic Loadings based on Experimental Tests

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ABSTRACT

The non-linear performances of RC beam specimens under flexure are evaluated with constant % of Thermo Mechanically Treated (TMT) reinforcement in confined and unconfined conditions by pushover and cyclic loading. The pushover and cyclic behavior of the beam specimens is plotted in the form of load-deformation for determining the non-linear modeling parameters as per ASCE/SEI 41-06. The beam specimens under cyclic testing have shown large yield strength but low ductility as compared to pushover testing. It may be concluded that the ductility, which is synonymously used without the relevance either of monotonic or cyclic load of a component or a structure, may result to be lethal if appropriation is neglected in behavior factor in seismic design. The confining of transverse reinforcement is another significant parameter on which the post-yield force–deformation relationship and the resulting ductility of an RC component depend.

## 1. Introduction

Ductility is one of the extremely important considerations regarding the seismic design of structures as the present seismic design philosophies rely on two major considerations i.e. energy absorption and dissipation of post-elastic deformation for survival during severe earthquakes. Structures incapable of behaving in a ductile fashion must be designed with much higher seismic efficiency in order to avoid collapse. Most building codes for seismic loading, however, recommend such structural designs which may resist relatively moderate earthquakes elastically. In the case of a severe earthquake, reliance depends on sufficient ductility after yielding that enables a structure to survive without collapse. Hence, the recommendations for seismic loading can be justified only if the structure possesses sufficient ductility to absorb and dissipate energy by post-elastic deformations when subjected to several cycles of loading far within the yield range. According to the current seismic design philosophies of moment resisting frame buildings, the ductile response may be possible if the principle of “strong column–weak beam” exists i.e. formation of plastic hinges in beams rather than in columns. The nature of plastic hinge in RC beam must be dominant by flexural behavior to accrue sufficient ductility in the structure. In this context, tensile flexure yielding should occur in reinforcing steel prior to crushing of concrete as in the case of under-reinforced concrete design. Therefore, strength and ductile characteristics of the reinforcing steel need to govern the post-yield failure pattern and mode of failure of the RC member. Surprisingly, these two main attributes of reinforcing bar are opposite to each other. Earlier, when plain reinforcing bars were used in constructions, the main hindrance was their low yield strength with adequate ductility. Hence, the designed RC section became more congested or sometimes difficult to accommodate the design reinforcement to resist the seismic demand in case of severe earthquakes. Since the recent past, HYSD (High Yield Strength Deformed Bars), also known as TOR (Twisted ORE Reinforcement), has continuously been used by virtue of high yield strength. But as the ductility of HYSD reinforcing bar is very low and increasing the strength ductility lowers. Therefore, IS 1893 [3] puts restriction on TOR reinforcement that the strength more than 415 MPa may not be used in seismic prone areas; however it has now been upgraded upto 500 MPa. This situation continued over the years until the development of TMT reinforcing bars. The structural characteristics of TMT reinforcing bars are such that the strength is provided at the outer core and ductility in the inner core i.e. both, strength and ductility are blended with each other. Therefore, TMT reinforcement has high strength and ductility as compared to companion reinforcement used in the past and at the present, the TMT reinforcement is being used by the construction industry. In the proposed study, pushover and cyclic testing of RC beam specimens with and without confinement has been carried out under flexure to evaluate the comparative post-yield behavior of specimens and their resultant ductility. The effect of confinement is also emphasized in this study.

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**Table 1**
Complete details of RC beam specimens under pushover and cyclic testing.

| SL | Specimen ID | Test type | Confinement condition | Reinforcement: Main (Φ)/shear (Φ) | Beam ast (%) |
|---|---|---|---|---|---|
| *TMT/G1 Specimens(Grade G1-20 mm)* | | | | | |
| 1. | *LBEAM-U1* | Pushover | Unconfined | TMT:20 mm/10 mm | 0.80 |
| 2. | *LBEAM-C2* | Pushover | Confined | TMT:20 mm/10 mm | 0.80 |
| 3. | *LBEAM-U3* | Cyclic | Unconfined | TMT:20 mm/10 mm | 0.80 |
| 4. | *LBEAM-C4* | Cyclic | Confined | TMT:20 mm/10 mm | 0.80 |
| *TMT/G2 Specimens(Grade G2-20 mm)* | | | | | |
| 5. | *LBEAM-U5* | Pushover | Unconfined | TMT:20 mm/10 mm | 0.80 |
| 6. | *LBEAM-C6* | Pushover | Confined | TMT:20 mm/10 mm | 0.80 |
| 7. | *LBEAM-U7* | Cyclic | Unconfined | TMT:20 mm/10 mm | 0.80 |
| 8. | *LBEAM-C8* | Cyclic | Confined | TMT:20 mm/10 mm | 0.80 |

The experimentally obtained load-deformation relationship has been idealized as per ASCE/SEI 41-06 for the determination of non-modeling parameters and the resulting ductility of RC beam specimens.

## 2. Early studies

A number of well planned studies were carried out in the past to investigate the effect of various constructional aspects in flexure members either by conducting monotonic pushover or cyclic loading. A few of them related to present study were conducted by Hwang and Scribner [1], Darwin and Nmai [2]; Marfia et al. [5], Tsonos [9]. Some of the studies on the flexure member underlined the effect of bond-slip, shear and flexure including confinement effect under static and fatigue loading were conducted by Altoubat et al. [12], Al-Hammoud et al. [13], Munikrishna et al. [14]. Some studies focused on the non-linear modeling and plastic hinge rotation of beams by Oehlers et al. [7], Fantilli et al. [6], Scott and Whittle [8], Carpinteri et al. [11], and Haskett et al., [15]. The present study focused on the behavioral difference of an RC component under the monotonic pushover static loading and cyclic loading and their plastic hinge parameters to simulate the non-linear behavior under the concept of "strong column–weak beam" mechanisms.

## 3. Evaluation of non-linear behavior of RC beam specimens under pushover and cyclic testing

The performance of eight beam specimens with constant 0.80% reinforcement has been tested under pushover loading and cyclic loading. The % of reinforcement is fixed on the basis that the specimens fail in flexure i.e. an under-reinforced beam specimen but more than the minimum % of reinforcements (i.e. 0.24 $\sqrt{\frac{f_{ck}}{f_y}}$) as recommended in IS 13920 [4]. All the beam specimens are cast in same aggregate, sand and water–cement ratio under similar environmental conditions to maintain uniform characteristic strength of concrete ($f_{ck}$) about 25 MPa. The purpose of the testing is to study the post-yield behavioral difference between monotonic non-linear pushover behavior and hysteretic behavior. The test program consists of casting of eight RC beam specimens of size 300 mm × 300 mm × 3.0 m with aspect ratio of 10 ($l/d = 10$), termed as L-beams. These beam specimens are constructed in Thermo Mechanical Treated (TMT) reinforcement under unconfined and confined conditions. TMT reinforcing bars are obtained from a Standard make in two grades i.e. TMT/G1 and TMT/G2. The complete scheme of beam specimens tested under pushover and cyclic testing is given in Table 1. The stress–strain test results of TMT reinforcement under uni-axial tensile test are summarized in Table 2. The complete reinforcement details along-with sectional details of beam specimens are given in Fig. 1 and the test set-up for pushover and cyclic loading are shown in Fig. 2.

The salient features of test set-up consist of (i) *Strong Floor* to fix the test setup firmly with the help of high tension bolts, (ii) *Reaction Wall* to apply the pushover and cyclic loads on the beam specimen with the help of, (iii) *Two Servo-Controlled Hydraulic Actuators* in synchronized mode. The one end of the actuators is connected to the middle portion of beam specimen and the other end is connected to reaction wall and (iv) *Mechanical Jacks* to restrain the beam specimens at both the ends so that no translation movement is possible; only rotation can occur as in the case of simple supported conditions. The loading history under pushover testing consists in the form of ramp loading of gradually increasing amplitude. In case of cyclic testing, loading is applied in the form of displacement control sine sweep wave at a very low frequency ($f = 0.0083$ Hz), as shown in Fig. 2. The amplitude of loading increases gradually in two phases i.e. phase 1 consists of 5 mm to 50 mm with an interval of 5 mm and phase II consists of 50 mm to 150 mm with an interval of 10 mm. These specimens are tested up to failure and their complete non-linear behavior in the form of load deformation diagram under both types of testing is recorded with the help of load cell and LVDT mounting on the actuator itself. The resultant load is the sum of the individual load of both the actuators while the resultant displacement is the average of individual displacement. Figs. 3 and 4 show the pushover and hysteresis behavior of typical beam specimens in different grades of reinforcement under unconfined and confined conditions. A comparison of pushover curves with envelope of hysteresis curves of different beam specimens is made in Fig. 5. Table 3 summarizes the evaluated parameters for the beam specimens on the basis of (a) Flexural capacity of beams i.e. yield capacity (Fy) and ultimate capacity (Fu), (b) Over strength factor (Fu/Fy), (c) Displacement ductility $\mu = (\delta u/\delta y)$ and finally (d) Energy dissipation (area under load deformation curve or cumulative area of load-deformation cycles). (See Table 4.)

The obtained hysteresis and pushover curves after the testing of specimens reveal that the cyclic ductility is comparatively 2 to 3 times lower than the ductility obtained from the pushover testing. It is mainly due to perfect yielding of reinforcement under flexure tension during increasing monotonic pushover loading while in cyclic loading the reinforcement suddenly fails in brittle manner after initial yielding. In pushover testing after initial cracking of concrete cover, the entire applied load is resisted by the reinforcement through the bond strength with the concrete. Therefore, bond-slip failure is also observed in unconfined specimens tested under the pushover testing. The bond-slip failure in the beam specimens is caused by a severe demand of the bond strength

**Table 2**
Stress–strain characteristics of TMT reinforcement under uni-axial tensile test.

| Reinforcement | | Yield | | Plateau | | Ultimate | | Fracture | | Strain energy (MJ/m$^3$) | Ductility $^{\varepsilon_u}/_{\varepsilon_y}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Type* | *Grade* | *Strain* | *Stress* | *Strain* | *Stress* | *Strain* | *Stress* | *Strain* | *Stress* | | |
| TMT | G1 | 0.0285 | 455.75 | 0.0507 | 467.82 | 0.1480 | 584.84 | 0.1754 | 411.18 | 83.838 | 5.195 |
| TMT | G2 | 0.0327 | 568.89 | 0.047 | 584.53 | 0.1106 | 672.44 | 0.135 | 430.82 | 71.065 | 3.631 |