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FLEXURAL DUCTILITY OF STRUCTURAL CONCRETE MEMBERS SUBJECTED TO LIMITED CYCLES OF REPEATED LOADING

NAZAR OUKAILI and MOHAMMED KHATTAB

Dept of Civil Engineering, University of Baghdad, Baghdad, Iraq

For structural concrete members that may expose to serious earthquake, overload or accident impact, the design of ductility must be given the same importance as the flexural strength. The aim of this investigation is to study the change in ductility of structural concrete flexural members during their exposure to limited cycles of repeated loading. Twenty full-scale beam specimens have been fabricated in to two identical groups; each group consisted of ten specimens. The first group was tested under monotonic static loading to failure and regarded as control beams, while the specimens of the second group were subjected to ten cycles of repeated loading with constant load interval, which ranged between 40% and 60% of ultimate load. Specimens in each group were categorized as follows: two traditional reinforced concrete specimens with different intensity of tension reinforcement; three partially prestressed specimens with bonded strands; three partially prestressed specimens with unbonded strands; and two fully prestressed concrete specimens. The main variable, which was considered for all specimens was the partial prestressing ratio (*PPR*). It was observed that, the ductility of reinforced concrete beams was insignificantly increased during subjecting to limited repeated loading. For fully prestressed and partially prestressed concrete beams with high level of *PPR*, the ductility was significantly enhanced, while, it was decreased for specimens with small level of *PPR*.

Keywords: Curvature, Deflection, Rotation, Flexural members, Bonded strands, Unbonded.

1 INTRODUCTION

Ductility assures gradual failure rather than brittle failure to provide a warning to the occupiers before total collapse. “The ductile structure is that one, which is capable to experience large inelastic deformations at near maximum load carrying capacity without brittle failure” (Thompson and Park 1980). For structural members, ductility is expressed usually in terms of deformation ductility ratio, which is described in terms of rotation, curvature and deflection (Naaman *et al.* 1986, Thompson and Park 1980 and Giannini *et al.* 1986). The ductility ratio is defined as the ratio of the ultimate deformation to the yield deformation (ACI 423-5R-99 1999).

The displacement ductility factor which is the value commonly used in nonlinear dynamic analyses is expressed as in Eq. (1):

$$\mu_\Delta=\Delta_u/\Delta_y \quad (1)$$

Where Δ_u = maximum deflection of the structure and Δ_y = deflection of the structure at first yielding.

Some analyses of structures have used the rotational ductility factor of members which is defined as in Eq. (2):

$$\mu_\theta = \theta_u / \theta_y \qquad (2)$$

Where θ_u = maximum plastic hinge rotation of the end of member and θ_y = rotation at the end of member at first yielding.

The essential information wanted by the designer concerns the required member section behavior at the plastic hinge expressed by the curvature ductility factor as in Eq. (3):

$$\mu_{\emptyset} = \emptyset_u / \emptyset_y \qquad (3)$$

Where $\emptyset_u$= maximum curvature at the section and $\emptyset_y$= curvature at the section at first yielding.

When calculating ductility factors for partially prestressed members, the description of the first yielding deformation (displacement, rotation or curvature) often causes difficulty when the load or moment-deformation curve is not elasto-plastic. In addition, it is not distinctive because the section contains both types of steel (prestressed and nonprestressed).

Cohn and Bartlett's (1982) anticipated that the yielding curvature accompanying with yielding of ordinary reinforcement. Thompson and Park (1980) proposed that, the yielding point is the intersection of the tangent of elastic portion of load-deflection curve and the horizontal line at the ultimate load. Park and Falconer (1983) took the yielding deformation at the intersection of the secant from zero to 75% of the ultimate moment capacity and the post elastic slope. Naaman *et al.* (1986) defined the yielding point as the intersection of secant from zero to the proportional limit of prestressed steel and the post-elastic slope.

All the above-mentioned methodologies are based on the ductility of the member at specific section rather than the yielding of specific components in the cross section.

2 THE EXPERIMENTAL PROGRAM

The experimental program was undertaken to study the ductility of partially prestressed concrete beams under monotonic static (S) and limited repeated loading (R).

This research included testing twenty simply supported structural concrete beams that have the same geometrical layout, same transverse reinforcement and variable longitudinal reinforcement. All beams were with (200 mm width × 300 mm height) rectangular cross section simply supported on a clear span of (3000 mm) length, where the span to total section depth ratio was 10. All beams were loaded in four-point loading scheme using two symmetrical monotonic concentrated static loads applied at one-third of the span length. These beams were divided into two identical categories. The first category was tested under monotonic static loading up to failure and regarded as controlled beams. The second category was exposed to repeated loading according to the following stages:

- Stage one: the minimum and maximum cyclic loads P_{min} and P_{max} were taken, respectively, as 40% and 60% of the ultimate load of the accompanying beams of first category. The load level was selected to simulate self-weight and self-weight plus superimposed dead load and service overload, respectively. Ten cycles of loading and unloading were implemented.
- Stage two: after ten cycles of repeated loading, the load was released to zero.
- Stage three: during this stage, beams were subjected to monotonic static loading until failure.

Each category consisted of ten beams divided into four groups as follows:

First Group – consisted of two conventional reinforced concrete beams (FR), one under-reinforced (UN) and the other with maximum reinforcement ratio (MAX). The Partially Prestressed Ratio ***PPR*** (Naaman *et al.* 1986) for these beams is zero.

Second Group – included three partially prestressed concrete beams (PP) with bonded strands (B). Each beam is reinforced with two Ø12.7 mm strands and the initial prestressing stress was equal to 0.7 of the characteristic strength (f_{pu}) of low-relaxation strand. Different amount of nonprestressing reinforcement was provided for each beam so as to get different value of ***PPR***. According to ACI-318-14 (2014), the first beam is categorized as tension-controlled (TC), while the second is transition-controlled (TRC) and the third is compression-controlled (CC).

Third Group – this group is identical to Second Group but with un-bonded strands (U). It comprised also three partially prestressed concrete beams with wide range of ***PPR*** value.

Fourth Group – consisted of two fully prestressed concrete beams (FP) with bonded strands, one is tension-controlled, and the other is compression-controlled. The first is reinforced with two strands and the other with three strands. ***PPR*** for these beams is one.

Figure 1 shows the typical reinforcement section and the transverse steel distribution along the member axis.

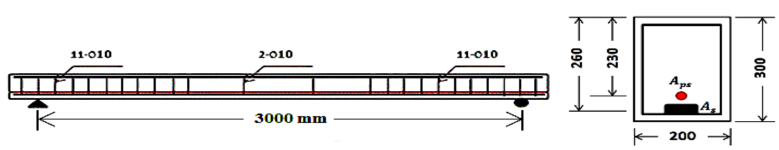

Figure 1. Transverse reinforcement distribution along member's axis and typical beam section.

The longitudinal reinforcement details of the tested beams are illustrated in Table 1. The beams were designed in such a way that the expected failure should occur due to flexure rather than shear, therefore steel stirrups of (Ø10 mm @ 100 mm) c/c were used in shear spans to guarantee that the beams will not fail under shear. The steel stirrups were tied to two longitudinal bars of (10 mm) diameter at the top (except FP-B-CC-S and FP-B-CC-R beams, they were provided with one strand and with initial prestressing stress equal to $0.5\ f_{pu}$) and to different number of mild steel bars at the bottom depending on whether the beam is tension controlled, transition or compression controlled. Yield stress of the longitudinal and the transverse bars was (570 MPa).

Table 1. Geometrical properties of steel used for reinforcing experimental beam specimens.

Beam's labelling	A_s (mm^2)	A_{ps} (mm^2)	A'_s or A'_{ps} (mm^2)	ω	ω_{ps}	$\acute{\omega}$	ϖ	***PPR***
FR-UN-S,R	4Ø12	-	2Ø10	0.043	-	0.043	0.000	0.000
FR-MAX-S,R	4Ø12+5Ø10	-	2Ø10	0.245	-	0.045	0.200	0.000
PP-B-TC-S,R	2Ø10	2 strands	2Ø10	0.043	0.185	0.043	0.185	0.771
PP-B-TRC-S,R	2Ø10+2Ø12	2 strands	2Ø10	0.124	0.178	0.043	0.259	0.529
PP-B-CC-S,R	6Ø12	2 strands	2Ø10	0.259	0.169	0.044	0.384	0.358
PP-U-TC-S,R	2Ø10	2 strands	2Ø10	0.043	0.152	0.043	0.152	0.743
PP-U-TRC-S,R	2Ø10+4Ø12	2 strands	2Ø10	0.172	0.143	0.044	0.271	0.409
PP-U-CC-S,R	2Ø10+5Ø12	2 strands	2Ø10	0.224	0.138	0.044	0.318	0.339
FP-B-TC-S,R	-	2 strands	2Ø10	0.000	0.187	0.049	0.138	1.000
FP-B-CC-S,R	-	3 strands	1 strand	0.000	0.240	0.000	0.240	1.000

Note: $\omega=\rho_s f_y/f'_c$; $\omega_{ps}=\rho_{ps} f_{ps}/f'_c$; $\acute{\omega}=\rho' f_y/f'_c$; $\varpi=\omega+\omega_{ps}-\acute{\omega}$ where $\rho_s=A_s/bd_s$; $\rho_{ps}=A_{ps}/bd_{ps}$; $\rho'=A'_s/bd_s$

The characteristic strength of prestressed low-relaxation strand was (1862 MPa) and the initial prestressing stress for all strands in all prestressed concrete beams was $0.7f_{pu}$ except for FP-B-CC-S and FP-B-CC-R, which was $0.6\ f_{pu}$. The compressive strength of the concrete cylinder at age 28 days used for all the beams was (40MPa).

The main objective of the present study is to investigate the effect of limited cycles of repeated loading on the ductility of reinforced, partially prestressed and fully prestressed concrete beams. Two parameters were studied with respect to ductility ratio; they were the Partial Prestressing Ratio (***PPR***) and the global reinforcing index ($\boldsymbol{\varpi}$).

3 THE EXPERIMENTAL RESULTS

The load-deflection diagrams for each two identical beams, (one from category 1 and the other from category 2), were compared (Figure 2).

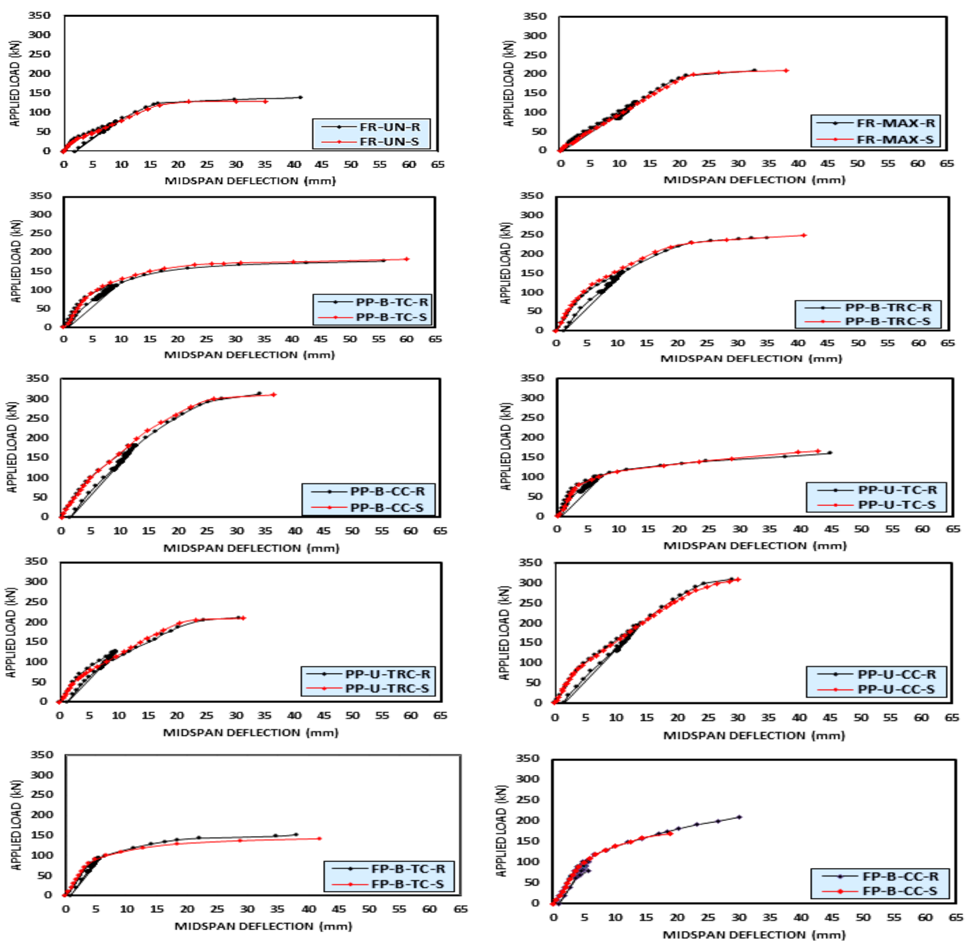

Figure 3. Load-deflection curves for the tested beams.

Reloading the beam with monotonically increasing static load, after releasing the tenth cycle of the repeated load, showed that the behavioral response of members under the applied load was approximately the same as for the identical counterpart beam in category 1 with little differences except for beams (FP-B-CC-S and FP-B-CC-R). It can be seen that for beams (PP-B-TC-S, R, PP-B-TRC-S, R, PP-U-TC-S, R and PP-U-TRC-S, R), three distinctive points could be observed. These points are characterized cracking, yielding and ultimate loads. This behavior is expected since they are designed as tension and transition-controlled beams, respectively. However, for (PP-B-CC-S,R and PP-U-CC-S,R) beams, where the behavioral response has different character regarding the load and the deflection at ultimate, only two points which characterized cracking and ultimate loads can be observed. Prior to cracking all beams behaved in an elastic manner.

Thompson and Park approach (1980), which is the most commonly used approach, has been adopted to determine the yielding deformation in the current study. Yield deflection, ultimate deflection and displacement ductility factor are illustrated in Table 2.

Table 2. Yield deflection, ultimate deflection and displacement ductility factor.

Beam's labelling	***PPR***	ϖ	**Yield deflection, Δ_y (mm)**	**Ultimate deflection, Δ_u (mm)**	**Displacement ductility factor, μ_Δ**	$\mu_{\Delta\ Repeated}/\mu_{\Delta\ Static}$
FR-UN-S	0.000	0.000	8.0	30.0	3.75	1.47
FR-UN-R			7.5	41.5	5.53	
FR-MAX-S	0.000	0.200	12.0	38.0	3.16	0.76
FR-MAX-R			13.5	32.5	2.41	
PP-B-TC-S	0.771	0.185	7.5	60.0	8.0	1.00
PP-B-TC-R			7.0	56.0	8.0	
PP-B-TRC-S	0.529	0.259	9.0	41.0	4.56	0.77
PP-B-TRC-R			10.0	35.0	3.50	
PP-B-CC-S	0.358	0.384	15.0	36.0	2.40	0.89
PP-B-CC-R			16.0	34.0	2.13	
PP-U-TC-S	0.743	0.152	6.0	43.0	7.17	1.23
PP-U-TC-R			5.1	45.0	8.82	
PP-U-TRC-S	0.409	0.271	11.0	31.0	2.82	1.21
PP-U-TRC-R			9.0	30.5	3.40	
PP-U-CC-S	0.339	0.381	12.0	30.0	2.50	0.91
PP-U-CC-R			12.5	28.5	2.28	
FP-B-TC-S	1.00	0.138	6.0	42.0	7.00	0.78
FP-B-TC-R			7.0	38.0	5.43	
FP-B-CC-S	1.00	0.240	8.0	18.5	2.31	1.53
FP-B-CC-R			8.5	30.0	3.53	

It was found that, the ductility ratio is inversely proportional to the reinforcing index (ϖ) for beams of the same type. In other words, the ductility factor increased when the reinforcing index decreased for FR, PP (bonded and unbonded) beams and for FP beams. That means increasing reinforcement (nonprestressed or prestressed) in the beam resulted in a considerable reduction in the ductility ratio. The case is different concerning the relation between ***PPR*** and the ductility ratio. The results show that the ductility ratio is directly proportional to ***PPR***. By studying the relation between the ductility ratio and the bonding properties, another observation can be distinguished. As shown from the Table 2, the ductility ratio is very close for both beams (PP-B-TC-S) and (PP-U-TC-S). The two beams are reinforced with the same prestressed and non-prestressed steel. The difference between the two beams is that the first one has bonded strands while the other has unbonded strands. Therefore, the ductility ratio is not affected by the bonding properties. The comparison between (PP-B-TC-S) and (FP-B-CC-S), which have approximately the same ultimate load strength is very interesting. Both beams have bonded strands but the first one is partially prestressed, whereas the second is fully prestressed. The partially prestressed beam (PP-B-TC-S) is more ductile than the fully prestressed beam (FP-B-CC-S). It means that presence of nonprestressed steel enhanced the ductility of prestressed concrete members. Ductility ratio was the same for beams PP-B-TC-S and PP-B-TC-R but it was increased due to repeated loading for beam PP-U-TC-R comparing with PP-U-TC-S by about 23%. It seems that the effect of repeated loading on beams with unbonded strands is more significant rather than beams with bonded strands. Repeated loading enhanced the ductility ratio of (FP-B-CC-R) beam comparing with the counterpart beam (FP-B-CC-S) by about (53%). The situation is different concerning ductility of beam (FP-B-TC-R). The ductility is decreased by about (22%) when the beam is subjected to repeated loading.

4 CONCLUSIONS

The following conclusions can be drawn:

- For all types of beams (FR, PP and FP), displacement ductility ratio ($\boldsymbol{\mu_{\Delta}}$) is inversely proportional to the reinforcing index ($\boldsymbol{\varpi}$) regardless of the type of testing (static or repeated). On the other hand, for partially prestressed beams, the ductility ratio is directly proportionated to Partially Prestressed Ratio (***PPR***).
- The effect of bonding between strands and concrete has little effect on ductility ratio for PP-beams type when they subjected to static loading.
- For FR beam with little amount of reinforcing index, the ductility ratio has been enhanced when this beam was subjected to repeated loading. The same thing can be said for tension-controlled with unbonded strands PP beam. The effect of repeated loading on tension-controlled with bonded strands PP beam is approximately zero.
- The repeated loading led to decreased ductility ratio for both types of PP compression-controlled beams (bonded and unbonded).
- Unexpected phenomenon has been noticed for compression-controlled FP beam. Although the prestressed steel area is increased comparing with tension-controlled FP-beam but the ductility ratio is increased when it was subjected to repeated loading. It seems that, decreasing the initial prestressing stress from $0.7f_{pu}$ to $0.6f_{pu}$ was the reason for that unexpected phenomenon.

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