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# Response of Reinforced Concrete Tapered Beams Strengthened Using NSM-CFRP Laminates

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***Keywords:***

Carbon Fiber Reinforced Polymer (CFRP); Near Surface Mounted (NSM); Tapered beams

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**A B S T R A C T**

The present study is about an experimental investigation of the strength and response of reinforced concrete tapered beams strengthened by near surface mounting (NSM)-CFRP technique. The influence of several parameters on the behavior of beams is investigated. And those parameters are: angle of inclination and strengthening patterns by NSM-CFRP technique. The experimental program involved testing nine specimens of reinforced concrete tapered beams and one prismatic beam. There were two groups in the experimental program; the first group included four unstrengthening reference beams to investigate the effect the angle of inclination, and the second group included six specimens were strengthened by NSM-CFRP strips with different strengthening patterns (U-strips) and (UL-strips) were used to strengthen the tapered beams against shear and flexural forces. The results of the experiments indicated that as the angle of inclination increased, from (0˚) to (7°), (14°) and (21°) decreases the ultimate load capacity (Pu) by about (4)%, (14)% and (41)% respectively for unstrengthen tapered beams, as well as the deflection at the ultimate load. Also, when compared unstrengthen with strengthened beams, the ultimate load capacity will increase with the angle of inclination increased, from (0˚) to (7°), (14°) and (21°), for (U-strips) patterns the percentages of increase were (7)%, (9)% and (33) % respectively, while (UL-strips) increased the ultimate load capacity by about (19)%, (19)% and (44)% respectively.

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# استجابة العتبات الخرسانية المسلحة المدببة المقواة باستخدام تقنية التركيب بالقرب من السطح

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## الخلاصة

الدراسة الحالية دراسة تجريبية لاستجابة العتبات الخرسانة المسلحة المدببة المقواة باستخدام تقنية التركيب بالقرب من السطح CFRP- (NSM). تم دراسة تأثير عدد من المتغيرات على سلوك العتبات، هذه المتغيرات هي: زاوية الميل وأنماط التقوية باستخدام تقنية NSM-CFRP اشتمل البرنامج التجريبي على اختبار تسع عينات من العتبات الخرسانية المدببة وعتبة موشورية واحدة. تم تقسيم البرنامج التجريبي إلى مجموعتين. احتوت المجموعة الأولى على أربع عتبات مرجعية غير مقواة للتحقق من تأثير زاوية الميل، وتم تعزيز المجموعة الثانية التي تحتوي على ست عينات باستخدام شرائط NSM-CFRP لتقوية العتبات المستدقة ضد القص والانحناء بأنماط تقوية مختلفة (U - شرائط) و (شرائط UL) أوضحت النتائج التجريبية أن زيادة زاوية الميل من (0˚) إلى (7 °)، (14 °) و (21 °) ستنقص من سعة الحمولة القصوى بحوالي (4) %، (14) %، (41) % على التوالي كما وتقلل من الانحراف عند الحمل النهائي .أيضًا، عند المقارنة بين العتبات غير المقواة مع المقواة، ستزداد سعة الحمولة القصوى مع زيادة زاوية الميل، من (0˚) إلى (7 °)، (14 °) و (21 °)، لأنماط شرائط (U) كانت نسب الزيادة (7) ٪، (9) ٪ و (33) ٪ على التوالي، بينما زادت (شرائط UL) من سعة الحمولة النهائية بنحو (19) ٪، (19) ٪، (44) ٪ على التوالي.

**الكلمات الدالة:** العتبات المدببة، التركيب بالقرب من السطح، التسليح بألياف الكاربون البوليمرية.

## 1. INTRODUCTION

In construction, tapered (or haunched) reinforced concrete beams or concrete beams of varying depths have been used. These beams are frequently used in a variety of projects, including mid-rise building beams, bridges with double cantilever hammer heads, and bridges that are continuous or simply supported, for both aesthetic and economic reasons as shown plate 1. Because of the following advantages over prismatic beams, structural engineers and architects frequently use non-prismatic beams: The ability to bridge longer spans with less depth has increased, With such beams, the use of concrete and steel reinforcing is more efficient, The building's weight is reduced for a certain vertical / lateral stiffness as a result of the efficient use of materials, Increased room for services such as cooling, heating, electricity and water, There are aesthetic concerns, just as there are in the case of a warehouse or a bridge [2-5]. However, in certain countries, such beams are not a typical structural solution in buildings due to the higher costs associated with their construction, which are linked to the need for skilled formwork and reinforcing steel. Generally, haunches near the supports are used to deepen beams in order to enhance the support moment, resulting in a considerable reduction in the span moment [6-7]. Near surface mounted (NSM) with carbon fiber reinforced polymer (CFRP) is a rather new strengthening technique with a lot of promise for improving the shear resistance of reinforced concrete (RC) beams that are at riskiness of collapsing due to shear failure in a brittle mode [8]. This technique is depended on introducing fiber reinforced polymer (FRP) bars or strips are inserted into pre-cut epoxy-filled grooves in the concrete cover of the beam's lateral faces [9-10].

**Plate 1.**RC tapered beam in the pier structure [11].

## 2. EXPERIMENTAL STUDY

### *2.1 Experimental Program*

The experimental program includes cast and test nine reinforced concrete (RC) tapered beams, six RC tapered beams have been strengthened patterns by NSM-CFRP strips technique, as well as three RC tapered beams without strengthened and one prismatic beam as reference beams Table 1.

### *2.2 Description of Beam Specimens*

The specimens of RC tapered beams have a total length of (1200) mm, a width of (200) mm and a varying height of (250) mm in midspan and linearly reduced according to the specimen's inclination angle (α) (7°, 14° and 21°) in order to be (195, 138 and 78.8) mm on tips respectively. The last prismatic beam measures (1200) mm in total length, (200) mm in width and (250) mm in height. All the beams have 2 ∅ 12mm flexural reinforcement in the corner, in the center 1 Ø 10mm, and in the compression chord of beams 2 Ø 6mm, with a compression cord of the same shape. Shear reinforcement also provided by Ø 6mm steel bars with various spacing [12]. Figs. (1-2) show the dimensions and reinforcement for each beam specimen. Plate 2 show details of molds. The beams were tested under one point loading with a clear span of (1000mm). Bearing plates under load with dimensions (200*200) mm are used to prevent concentration load (local concrete crushing) [4, 7, 14, 15].

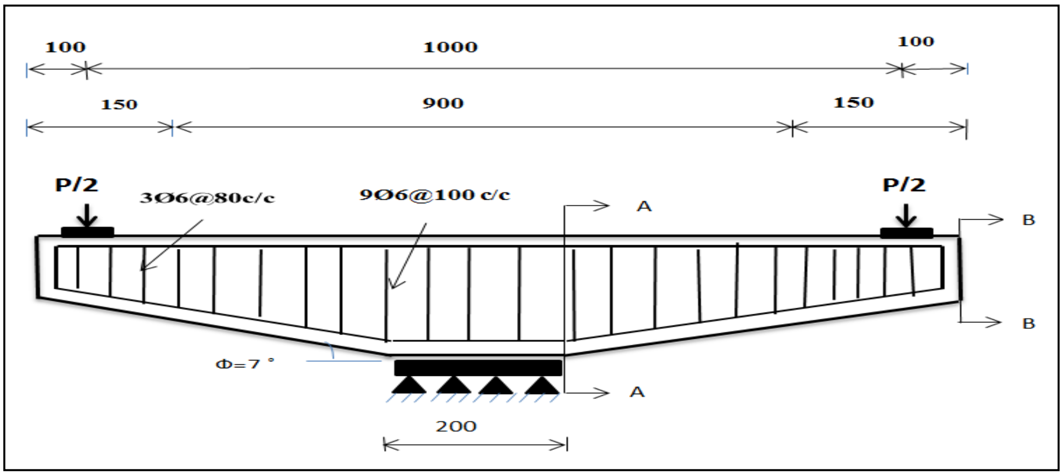


**Fig. 1.** Details of tapered beam (all dimensions in mm)

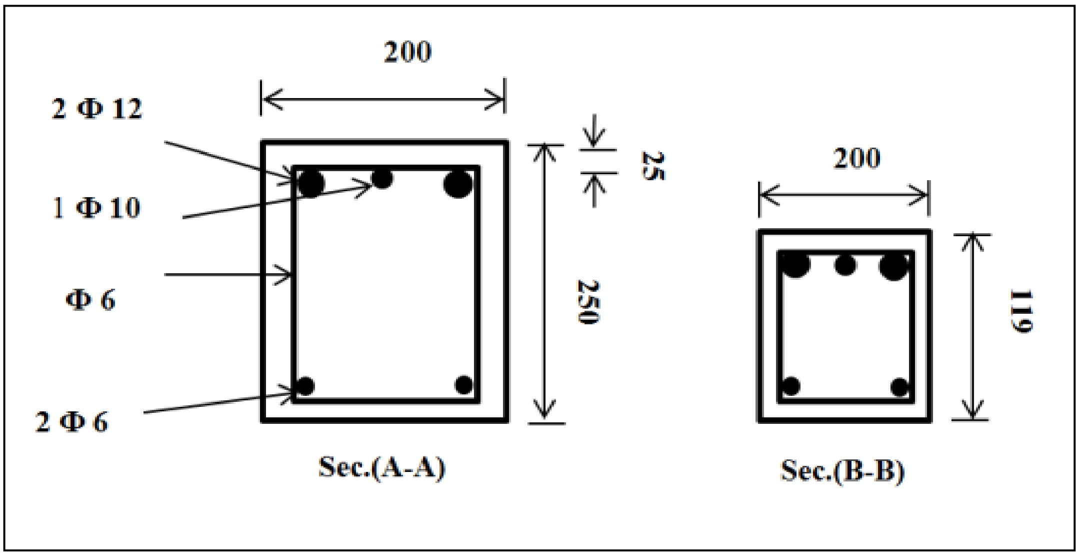


**Fig. 2.** Cross section for beam specimen.

**Table 1.**
Beam specimen's details.

| Beam Designation | Shape of Beam | Configuration for strengthening by (NSM-CFRP) technique. |
|---|---|---|
| **PB-0** | Prismatic | No strengthening |
| **TB7-0**<br>**TB14-0**<br>**TB21-0** | Tapered | No strengthening |
| **TB7-U**<br>**TB14-U**<br>**TB21-U** | Tapered | Six diagonal side strips (U- strips) |
| **TB7-UL**<br>**TB14-UL**<br>**TB21-UL** | Tapered | Six diagonal side strips and two longitudinal strips in the top (UL-strips) |

* **TB:** Tapered beam. **PB:** Prismatic beam. **7,14,21:** the inclination angle value (α).
**U:**side strips on the diagonal. **UL:** diagonal side strips and longitudinal strips .

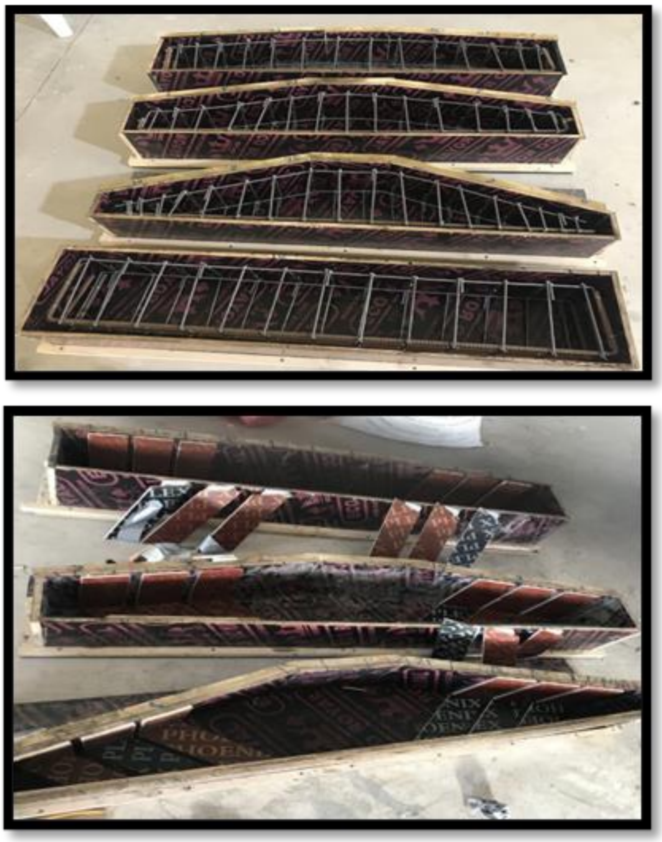

**Plate 2.** Details of molds

## 3. MATERIALS

The test specimens were manufactured from a variety of raw materials; the properties and descriptions of the materials used are listed in Tables (2-3) summarize the quantities of materials required for concrete mixtures.

**Table 2.**
Construction materials properties

| Material | Specification |
|---|---|
| **Cement** | Ordinary Portland cement (Type I) [16] |
| **Fine aggregate (Sand)** | Natural sand passed through (4.75) mm sieves [17] |
| **Coarse aggregate (gravel)** | river gravel had a maximum size of 14mm |
| **Water** | drinking water (tap water) |
| **Steel Reinforcement** | (ϕ12mm) deformed steel bar, yield strength (fy)(540MPa)<br>(ϕ10mm) deformed steel bar, yield strength (fy)(528MPa)<br>(ϕ6mm) deformed steel bar, yield strength (fy)(498MPa) [17] |

**Table 3.**
Proportions of concrete mix

| Material | Content |
|---|---|
| **Cement (kg/m3)** | **466** |
| **Fine aggregate (Sand) (kg/m3)** | **750** |
| **Coarse aggregate(gravel) (kg/m3)** | **969** |
| **Water(kg/m3)** | **191** |
| **w/c (%)** | **0.41** |

*Compressive strength of concrete ($f_{cu}$) (at 28days) is (46.3) MPa, modulus of rupture ($f_r$)is (5.6) MPa.

## 4. NEAR SURFACE MOUNTED (NSM) TECHNIQUE INSTALLATION

To ensure that the measured dimensions were obtained accurately, grooves were made at the located regions of beam faces to place the CFRP strips during the casting procedure, where the Plywood pieces with a thickness of (5) mm were placed, after determining their exact locations and following the work plan, cut according to the required strip width (75) mm Three pieces of wood were placed in a U-shape at each end of the beam in a direction perpendicular to the expected shear cracks of the inclined shear forces, with a space of (30) mm between them and at an angle of (45°) to ensure the beam's strength against these forces [5, 10]. In addition to the oblique shear reinforcement, some of the beams were strengthened against bending forces, where two wood pieces were positioned to form two grooves from the tension chord along the beam, as shown in the Fig. 3. The strengthening by NSM-CFRP technique procedure is as follows:

**1-** The grooves were cleaned with a brush and water to remove dust and any loose material.

**2-** After being measured, the CFRP strips were cut to the required length. CFRP strips make in various widths and lengths, as well as different configurations: six U-shaped or diagonally side strips for shear, and for the bending moment, strips in the tension two faces, as shown in the Plate 3.

**3-** The epoxy is applied with a painting brush after filling the groove to half depth with epoxy, then the CFRP strips were then gently inserted and pushed to allow the adhesive ingredients to flow around at the CFRP. After installing the CFRP strips, the application was completed by put on more adhesive material to completely fill the grooves and leveling the surface, as shown in the Plates 3.

**4-** The specimens were kept in the laboratory for a week before being tested.

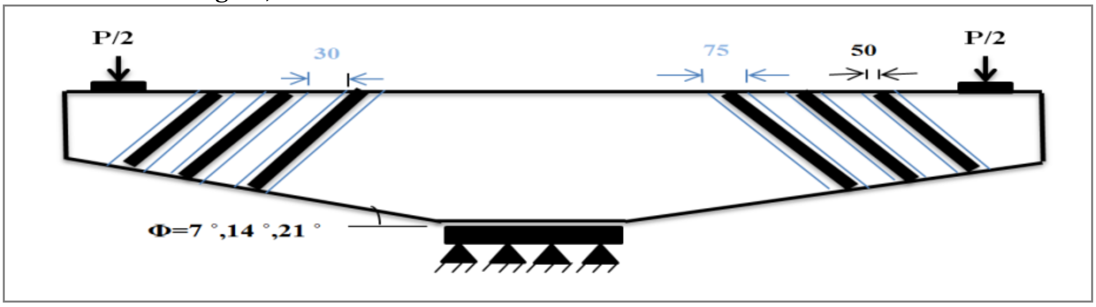


**Fig. 3.** Details of the tapered beam strengthened by (NSM) technique.

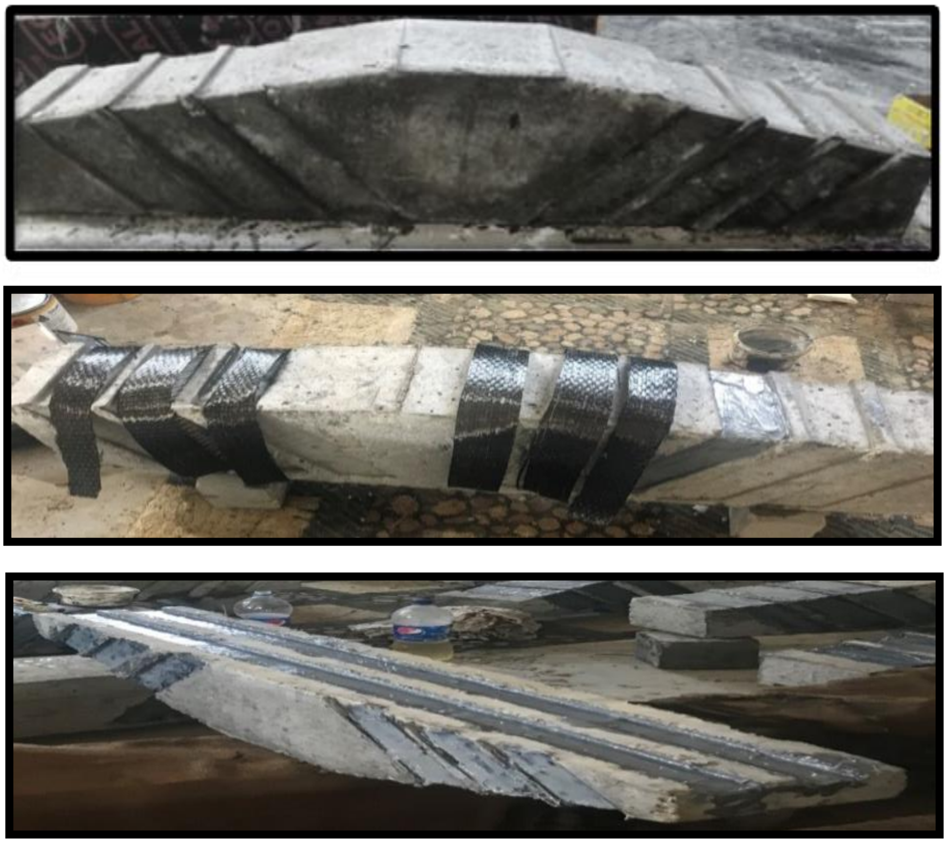

**Plate 3.** Process of the CFRP installation in the grooves.

## 5. TEST SETUP AND INSTRUMENTATION

At the age of 28 days, all beams and control specimens were removed from the curing process. Before the testing day, the specimens are cleaned and painted white color to make clear the crack propagation. A label is attached to each specimen. Loading points and the position of the dial gauge were also marked. The beams were simply supported by a stiff steel frame on both ends. The inverse position of the beams on the machine is shown in Plate 4. A load cell was used to measure the applied force, and a (LVDT) was attached to the top of the specimen to measure the midspan deflection. A data logger was used to record the results of the test (i.e., load and mid-span deflection).

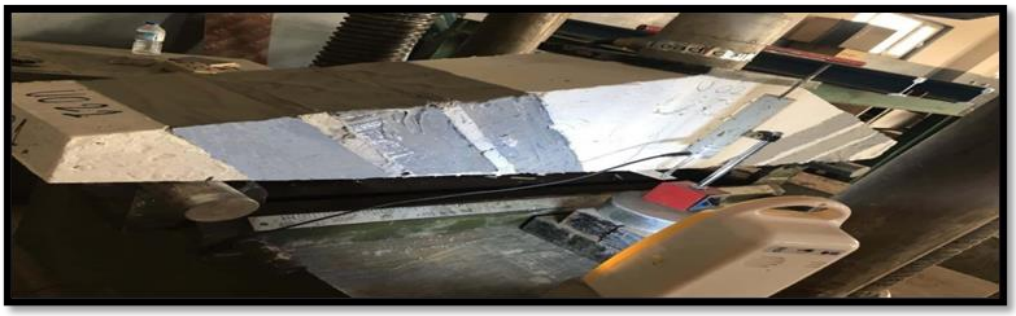

**Plate 4.** Test procedure.

## 6. TESTS RESULTS

Table 4 presents summarizes of the experimental results of tapered beams that have been tested.

**Table 4.**
Specimens Test Results.

| Beam Designation | $P_{cr}$ (kN) | $\Delta_{cr}$ (mm) | $P_u$ (kN) | $\Delta_u$ (mm) | Mode of Failure |
|---|---|---|---|---|---|
| **PB-0** | 50 | 2.344 | 200.59 | 18.69 | Flexural-shear failure |
| **TB7- 0** | 49 | 1.59 | 192.49 | 15.82 | Flexural-shear failure |
| **TB 14- 0** | 48 | 1.337 | 173.01 | 8.60 | Diagonal Shear Crack |
| **TB 21-0** | 50 | 2.7 | 118.75 | 5.31 | Diagonal Shear Crack |
| **TB7-U** | 40 | 1.453 | 205.45 | 21.86 | Flexural-shear failure |
| **TB14-U** | 42 | 1.69 | 188.76 | 31.63 | Flexural-shear failure |
| **TB21-U** | 39 | 0.935 | 157.7 | 19.46 | Flexural failure |
| **TB7-UL** | 45 | 3.115 | 228.28 | 35.06 | Flexural failure |
| **TB14-UL** | 60 | 2.39 | 223.9 | 30.08 | Flexural failure |
| **TB21-UL** | 48 | 2.464 | 171.57 | 21.02 | Flexural failure |

*$\mathbf{P_u}$: ultimate load, $\mathbf{\Delta_u}$: mid span deflection at ultimate load, $\mathbf{P_{cr}}$ : applied load at first crack, $\Delta_{cr}$: midspan deflection at first crack.

### *6.1. Load and Deflection at First Crack*

For the reference prismatic beam and the reinforced concrete tapered beams, Table 4 shows the values of the first crack loads. The first crack loads were in the range of (39 to 60) kN.

### *6.2. Tests Results of Un-Strengthening Specimens*

#### *6.2.1. Ultimate Load ($P_u$)*

During the examination of the resistance of the unstrengthening beams, the values of the ultimate load are shown in Fig. 4. The variation in the inclination angle has a clear effect on the beams' carrying capacity. When comparing the reference prismatic beam to the tapered beams, as the angle of inclination increases, the load-carrying capacity of the applied loads was decrease with the percentages (4%), (14%) and (41%) for TB7-0, TB14-0, and TB21-0 respectively.

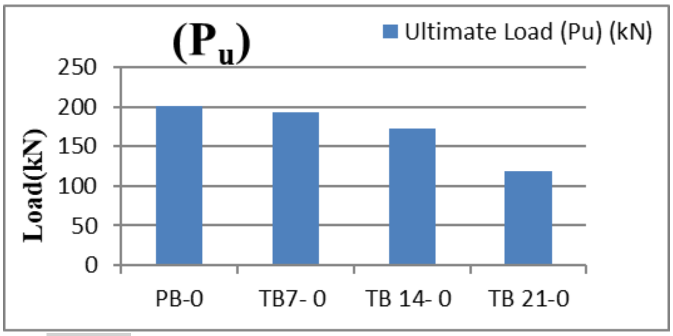


**Fig. 4.** Unstrengthened specimens ultimate load.

#### *6.2.2. Deflection at Ultimate Load ($\Delta_u$)*

Fig. 5 shows the deflection values of the unstrengthening specimens at the ultimate load. It is clear that the variation in the inclination angle has a clear effect on the deflection at the ultimate load values. When the reference prismatic beam and the tapered beams are compared in deflection at the ultimate load, presents that with an increase in the inclination angle, the values of the deflection at the ultimate load decrease, because the load-carrying capacity of the applied loads also decreases, therefore the deflection also decreased with the percentages (15%), (54%) and (72%) for TB7-0, TB14-0 and TB21-0 respectively.

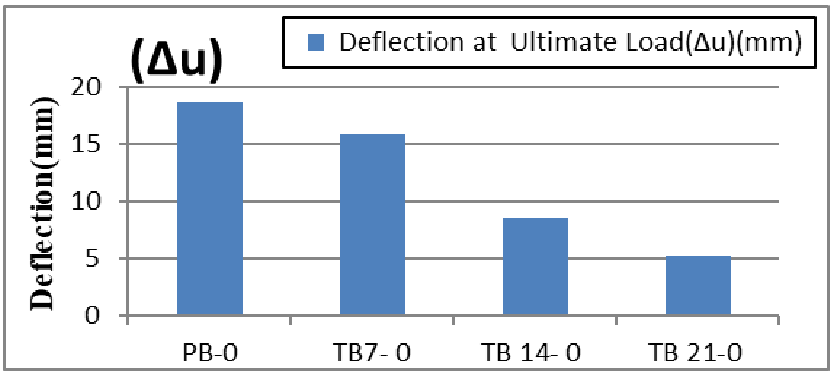


**Fig. 5.** Deflection of the unstrengthened specimens at the ultimate load.

### *6.3. Strengthening Effect*

The beams were compared on the basis of classification the beams according to the variables inclination angle to determine the effect of strengthening on tapered beams, and the strengthened patterns by NSM-CFRP technique.

#### *6.3.1 Ultimate Load ($P_u$)*

By comparing the capacity of the ultimate loads for the unstrengthened reference tapered beams with the strengthened reference tapered beams shown in Fig. 6 , the comparison is based on the similarity of the angle of inclination, we notice that there is an increase in the ultimate load ratio of the strengthened specimens and the results were as follows: For (U-strips) and (UL-strips) strengthened patterns beams respectively, the ultimate load ($P_u$) will increase with the percentage (7, 19)%, (9, 29)% and (33, 44)% for the beams with inclination angle (7°), (14°) and (21°) respectively. The reason that the ultimate load capacity for specimens with strengthening by (NSM-CFRP) technique (UL-strips) pattern is the highest percentages of increase which is the strengthening continuous on three sides of the beam section (two laterals and the bottom ) also two longitudinal strips in the top help to increase the beam's shear and flexural capacities. This increase in load capacity could be due to the increased stiffness and crack restriction caused by the use of CFRP strips as an external strengthening material. It can also be seen from Figs. (7, 8, 9) the effect of the form of strengthening by NSM-CFRP technique. The specimens with the strengthening pattern (UL- strips). They had higher percentages of increase than the strengthening pattern (U- strips) for the specimens that have a similar angle of inclination.

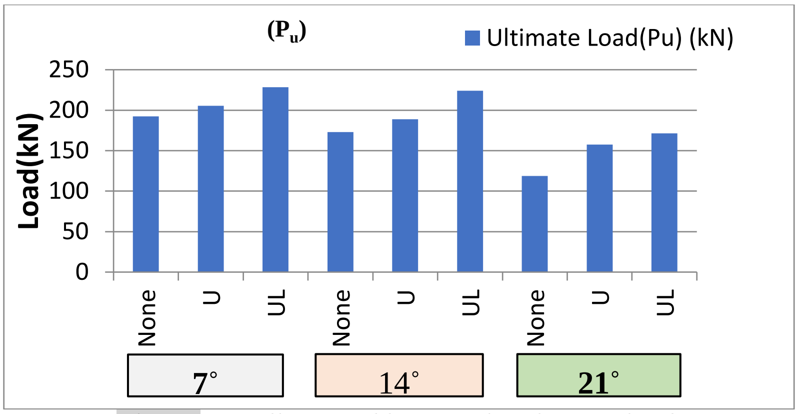


**Fig. 6.** For all tapered beams, the ultimate load.

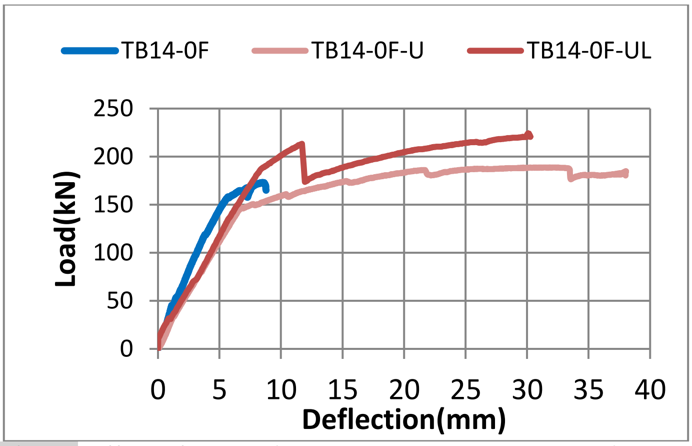


**Fig. 7.** Effect of strengthening using NSM-CFRP technique on load- deflection curves for beams (α =7˚)

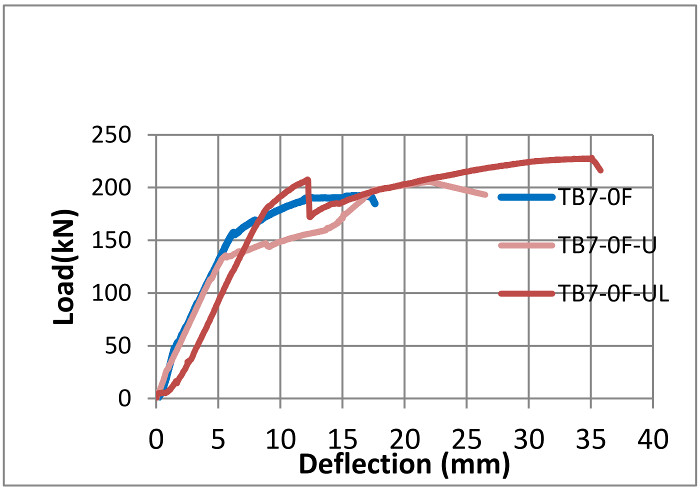


**Fig. 8.** Effect of strengthening using NSM-CFRP technique on load- deflection curves for beams (α =14˚)

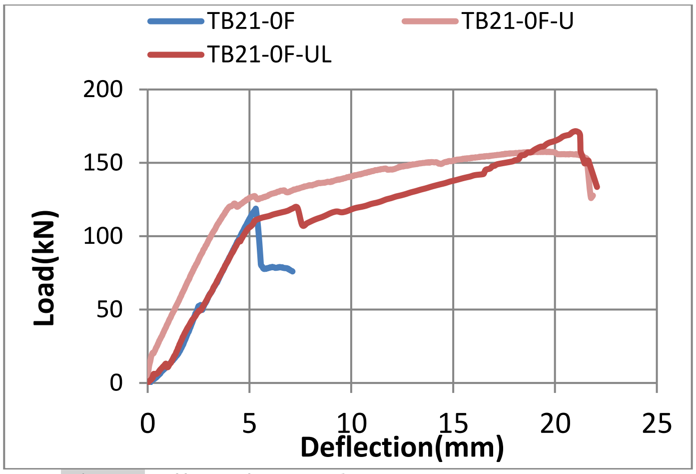


**Fig. 9.** Effect of strengthening using NSM-CFRP technique on load- deflection curves for beams (α =21˚)

### *1.1.1. Deflection at Ultimate Load ($\Delta_u$)*

The deflection values of the tested specimens at ultimate load are shown in Fig. 10. At ultimate load, the deflection values ranged from (5.31 to 35.06) mm.

Generally, when compared to unstrengthened specimens with (NSM-CFRP) technique (U-strips) and (UL-strips) strengthened patterns show lower deflections at the same ultimate load's levels.

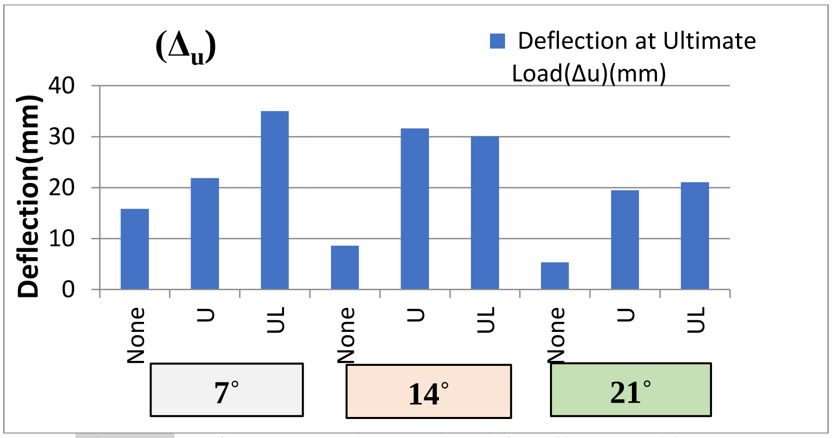


**Fig. 10.** Deflection at ultimate load for all tapered beams.

## *1.2. Effect of Inclination Angle*

### *1.2.1. Ultimate Load ($P_u$)*

The inclination angle has a considerable effect on the beams' carrying capacity. Generally, as the inclination angle increases from (0°) to (7°), (14°), and (21°), the carrying capacity of the applied loads decreases by a certain percentage due to the decrease in concrete volume. But, when compared to the decrease in concrete volume, it remains a good percentage. However, the reduction in beam strength is not proportional to the reduction in beam volume. As shown in Fig. 11, increasing the inclination angle from (7°) to (14°) and (21°), respectively, reduces the carrying capacity of the applied loads, as well as the following results: The ultimate load ($P_u$) for unstrengthening beams decreases as the percentage (10)%, (38)%. The ultimate load ($P_u$) for beams strengthened using the (NSM-CFRP) technique (U-strips) pattern will decrease by a percentage of (8%), (23%).The ultimate load ($P_u$) for beams strengthened using the (NSM-CFRP) technique (UL-strips) pattern will decrease by a percentage (2)%, (25)%.

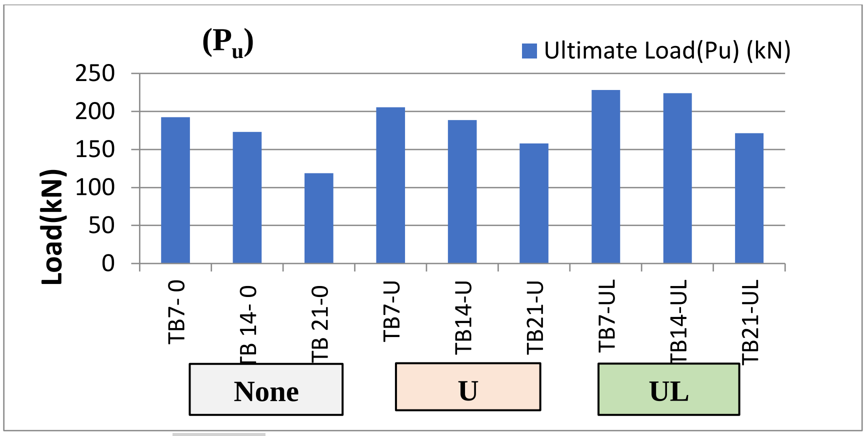


**Fig. 11.** Ultimate load for all tapered beams.

### *1.2.2. Deflection at Ultimate Load ($\Delta_u$)*

As shown in Fig. 12 the increasing the inclination angle from (7°) to (14°) and (21°) respectively reduces the values of deflection at the ultimate load and the following results: the deflection value at the ultimate load ($\Delta_u$) for unstrengthening beams decreases with the percentage (46)%, (66)%. The deflection value at the ultimate load ($\Delta_u$) for beams with strengthened using (NSM-CFRP) technique (U-strips) pattern, decreases with the percentage (11)% whenever the inclination angle was (21˚) but when the inclination angle(14˚), the deflection value at the ultimate load ($\Delta_u$) will increase with the percentage (45)%. The deflection value at the ultimate load ($\Delta_u$) for beams with strengthened using (NSM-CFRP) technique (UL-strips) pattern, decreases with the percentage (14)%, (40)%.

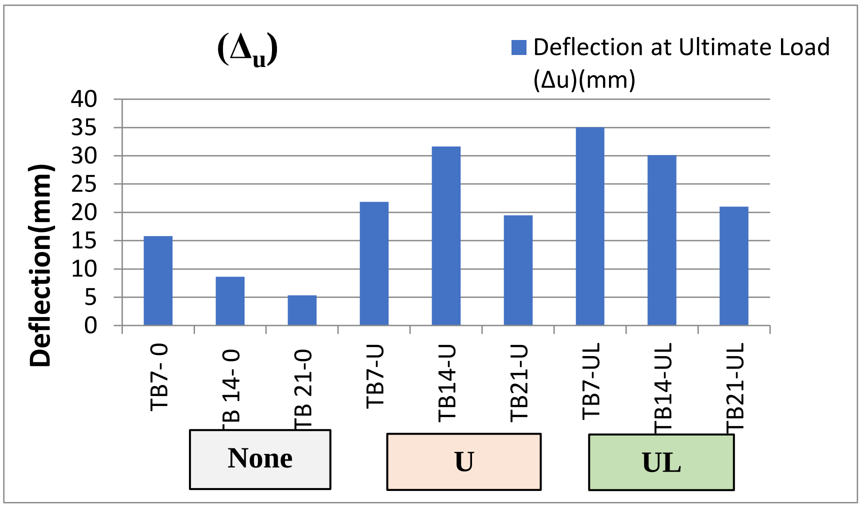


**Fig.12.** Deflection at ultimate load for tapered beams.

## 2. MODES OF FAILURE

Table 4 and plate 5 show the modes of failure for all tested beams. The modes of failure for the reference beams as follows: (PB-0) and (TB7-0) beams had a combination of straight and diagonal cracks ran the length of the middle third span (Flexural-shear failure). The failure mode of (TB14-0) beam was (shear failure), while (TB21-0) beam was diagonal shear. The failure modes for the beams strengthened using NSM-CFRP technique, (TB7-U, TB14-U, TB21-U, TB7-UL, TB14-UL, TB21-UL) were nearly identical, Under the applied load, the first crack appears in the middle of the beam. Then, below the applied load, several new cracks have appeared, extending from the tension area at the bottom of the beam to the compression area at the top of the beam. Some of them were straight while others were diagonal, with the continuation of load, these cracks expand until failed of the beam. Generally, the use of CFRP strips prevented the expansion of diagonal cracks, as well as a result of the shear span's strengthening, when compared to the previous control non-strengthened beams, the length and number of flexural cracks increased. Some of the tested beams displayed crushing signs in the compression zone after failure due to excessive loading [20, 24].

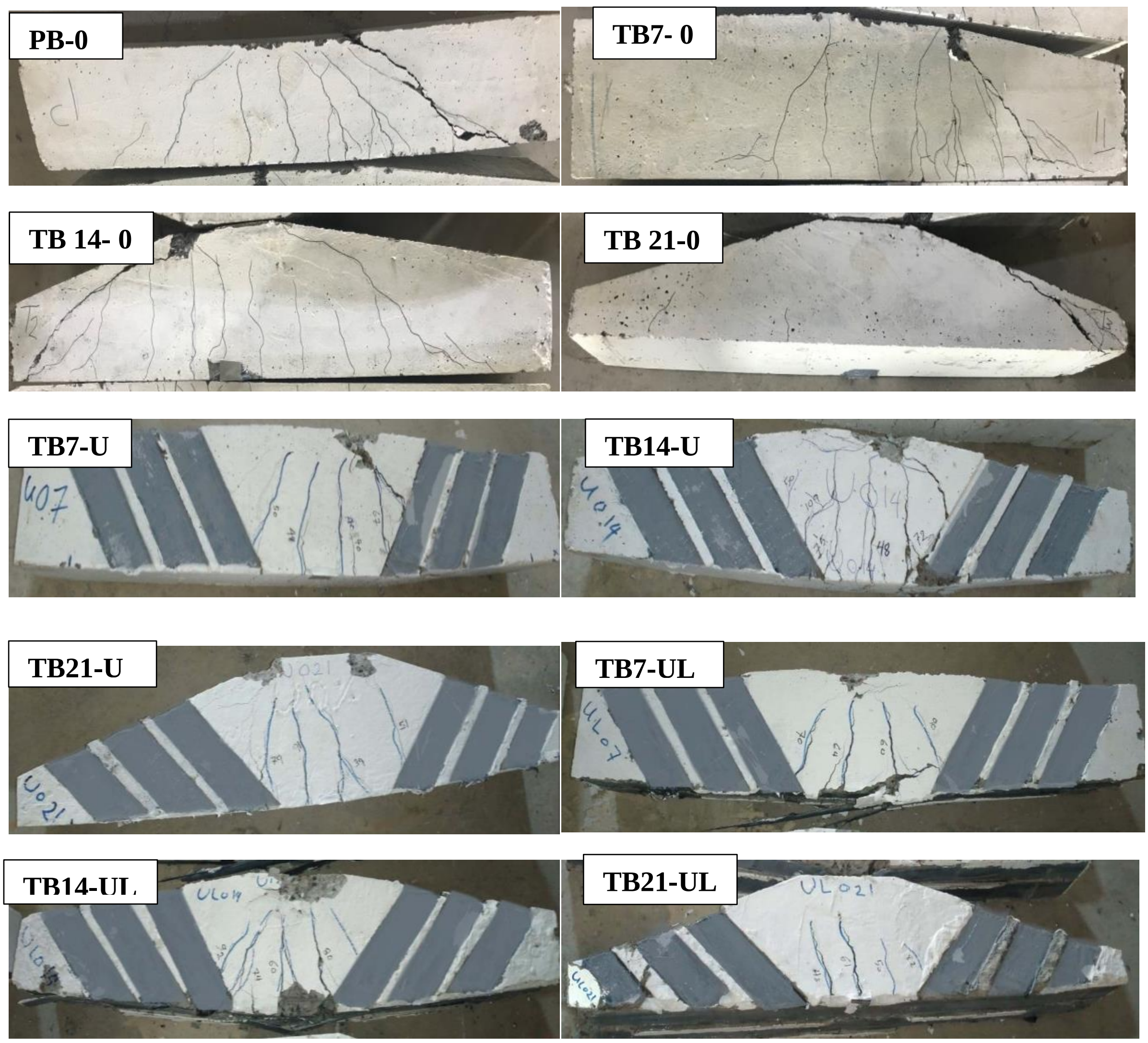


**Plate 5.** Cracking patterns of the tested beams.

## 3. CONCLUSIONS

1. For unstrengthed tapered beams ,increasing the inclination angle from (0°) to (7°), (14°) and (21°) decreases the ultimate load capacity ($P_u$) by about (4)%, (14)% and (41)% respectively.
2. In the case of strengthened using NSM-CFRP technique (U-strips) and (UL-strips) strengthened patterns beams respectively the comparison is based on the angle of inclination being similar with unstrengthened tapered beams. Increase the ultimate load capacity ($P_u$) with the percentage (7, 19)%, (9, 29)% and (33, 44)% for the inclination angles (7°), (14°) and (21°) respectively.
3. The use of CFRP strips reduced the diagonal crack propagation, while the length and number of flexural cracks increased as a result of the strengthened shear span.
4. At mid-span, NSM–CFRP (UL-strips) pattern strengthened specimens failed suddenly by de-bonding and explosive rupture of two CFRP strips in the tension face, followed by a failure in beam.
5. Because that the first crack load value is a function of concrete properties, it is generally not affected by increasing inclination angles of tapered beams.

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