# EXPERIMENTAL STUDY OF BEHAVIOR OF REINFORCED CONCRETE SLABS UNDER IMPACT LOADING

# دراسة عملية لسلوك البلاطات الخرسانية المسلحة تحت الاحمال الصدمية

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## ABSTRACT :

An experimental program to study the behavior of reinforced concrete slabs under impact loading was carried out through this work . Experimental work included testing of fifteen two-way reinforced concrete slabs , three of which were tested under central concentrated static loads while the others were tested under impact loading by means of a falling mass at the center of the slab .A steel ball of (90mm) diameter and (3 kg) weight was used as a falling mass for all the impact tests.

The main test variables in this study were: dimensions of the slabs , reinforcement ratio, height of fall of the striking object and support conditions of the slab. The maximum transient and residual central deflections were measured in each impact test using linear variable differential transformer(LVDT).It was found that the central deflections are proportional to the height of fall of the striker at low heights(less than 600 mm)for all tested slabs under impact loads. These deflections were found to be much larger with a slight increase in height of fall of the striker ( almost a double value of deflections was noticed at an increase in fall of less than 25 % beyond 600 mm height of fall ). Also ,it was found that , with the repetition of strikes and as the falling height of the striking object increases , cracks at the bottom faces of all slabs starts prior to those at the top face . However , cracks do not propagate longitudinally or widen with the increase of heights of falls but rather scabbing of the concrete starts to form with large pieces of concrete scabbs out at larger drop height .

**Keywords**: impact testing , drop-weight , reinforced concrete , slabs

## الخلاصة :

تم إجراء برنامج عملي لدراسة سلوك البلاطات الخرسانية المسلحة تحت الأحمال الصدمية. إن الفحوصات العملية تضمنت اختبار خمسة عشر بلاطة خرسانية مسلحة ، ثلاثة منها فحصت تحت الأحمال الستاتيكية ( static loads ) المسلطة في مركز البلاطة الخرسانية وبقية البلاطات فحصت تحت الأحمال الصدمية ( impact loads ) بواسطة ثقل ساقط في مركز البلاطة . استخدمت كرة حديدية صلبة ذات قطر ( 90 ملم ) ووزن ( 3 كغم ) في جميع الفحوصات الصدمية .

إن متغيّرات الاختبار الرئيسية في هذه الدراسة كانت: أبعاد البلاطات، نسبة التسليح، ارتفاع السقوط للجسم الصادم وحالة المساند للبلاطة. تم قياس الانحرافات المركزية القصوى والانحرافات المتبقية في كل فحص تحت الحمل الصدمي باستخدام المحول التفاضلي المتغير الخطي ( LVDT ). وُجد بأن قيمة الانحرافات المركزية تتناسب مع ارتفاع الكتلة الساقطة عند الارتفاعات المنخفضة ( أقل من 600 ملم) في جميع البلاطات المفحوصة تحت الأحمال الصدمية. تبين بأن تلك الانحرافات تكون اكبر كثيرا عند زيادة طفيفة في ارتفاع السقوط ( لوحظ بأن الانحرافات قد تصل إلى قيمة مضاعفة تقريبا عند زيادة ارتفاع السقوط بأقل من 25 % ما بعد 600 ملم ) . أيضاً وُجد بان تكرار الضربات وزيادة ارتفاع السقوط للجسم الصادم يؤدي إلى ظهور الشقوق في الوجه السفلي للبلاطات قبل الوجه العلوي. على أية حال فان هذه الشقوق لا تتكاثر طوليا أو عرضيا عند زيادة ارتفاع السقوط ولكن تحدث عملية تقشر في الخرسانة ( scabbing ) وتتطاير قطع من الخرسانة عند ارتفاع السقوط الكبير .

## INTRODUCTION :

Impact loading is recognized as the load resulting from collision between two bodies during a very small interval of time . The impact load applied to a structure depends on the striker velocity, the structure and the striker masses, the resulting deformations and the material properties of both bodies.

Some common examples of impact loading in the field of civil engineering are :vehicle collision with a structure , impact accidents during construction process, ships collision with offshore structures or gravity platforms , blows on concrete piles during driving , rocks falling on roof of protection shelters, aircraft collision with structure , etc. [1].

The experimental investigations on reinforced concrete slabs under impact loads are of fundamental importance because the impact load effect on these structures are complex and precise theoretical solutions are rarely available .

In this study , impact tests were used to obtain precise results on the structural behavior of concrete slabs under impact loads.

## EXPERIMENTAL WORK :

### Test Specimens :

Test specimens were divided into three groups according to the specimen dimensions . Slabs of group “1” have dimensions of ( 1000 x 600 x 50 mm ) , group “2” dimensions are ( 1000 x 1000 x 50 mm ) while group “3” are of ( 1000 x 1400 x 50 mm ). These dimensions were selected such that construction of slabs to be easy and their weights to be reasonable for lifting and testing .

Each group consisted of five specimens , one specimen was tested under static load while the others were subjected to impact loading by means of a falling mass at the center of the slab . The main test variables in the present study were : dimensions of the slab , reinforcement ratio of the slabs , height of fall of the striking object , support conditions of the slab.

Details of the test specimens including test type are shown in **Table 1**.

Table 1: Details of test specimens

| Group No. | Slab Dimensions (mm) | Slab No. | Type of Test | Support Condition | Reinf. Ratio % |
|---|---|---|---|---|---|
| 1 | 1000x600x50 | S11 | Static | Simply Supp. | 1.18 |
| | | D12 | Dynamic | Simply Supp. | 0.59 |
| | | D13 | Dynamic | Simply Supp. | 1.18 |
| | | D14 | Dynamic | Clamped | 1.18 |
| | | D15 | Dynamic | Simply Supp. | 1.77 |
| 2 | 1000x1000x50 | S21 | Static | Simply Supp. | 1.18 |
| | | D22 | Dynamic | Simply Supp. | 0.59 |
| | | D23 | Dynamic | Simply Supp. | 1.18 |
| | | D24 | Dynamic | Clamped | 1.18 |
| | | D25 | Dynamic | Simply Supp. | 1.77 |
| 3 | 1000x1400x50 | S31 | Static | Simply Supp. | 1.18 |
| | | D32 | Dynamic | Simply Supp. | 0.59 |
| | | D33 | Dynamic | Simply Supp. | 1.18 |
| | | D34 | Dynamic | Clamped | 1.18 |
| | | D35 | Dynamic | Simply Supp. | 1.77 |

## Steel Reinforcement :

The concrete slabs specimens were reinforced with (∅ 5 mm) and (∅ 8 mm ) reinforcing bars as main reinforcement. Three samples for each bar size were tested for evaluation of reinforcing yield stress and ductility. Test results for the used reinforcement bars are shown in **Table 2**.

Three different steel ratios ( ρ ) were considered in the tested slabs. These ratios and the corresponding bar size and spacing between bars are shown in **Table 3**. For each specimen , the reinforcing steel ratio was taken to be identical in both directions of the slab . Details are given in **Fig.1**.

Table 2 :Test results for the used reinforcement bars*

| ∅ (mm) | ∅ equivalent | Weight (kg/m) | $A_s$ ($mm^2$) | $f_y$ (MPa) | $f_u$ (MPa) | Elongation (%) |
|---|---|---|---|---|---|---|
| 5 | 4.984 | 0.153166 | 19.511 | 650 | 744 | 5 |
| 8 | 7.771 | 0.37233 | 47.43 | 543 | 670 | 10 |

*Steel reinforcement were tested at the structural laboratory in Baghdad University.

Table 3 :Steel reinforcement details of the tested slabs

| Steel ratio ( % ) | Bar dia. (mm) | Spacing between bars for slab (mm ) |
|---|---|---|
| 0.59 | 5 | 100 |
| 1.18 | 8 | 120 |
| 1.77 | 8 | 80 |

## Concrete :

Concrete was designed to give at( 28 )days a compressive strength of (25 MPa )of cylinder .A mix design was made according to the ACI committee 211.1.91 Manual [2].Some trial mixtures were carried out to get the required concrete strength. After that , the mix proportion by weight was achieved and used in this work . The mix proportion for ( 1 $m^3$ ) of concrete are given in **Table 4**.

Table 4 : Mix proportions for ( 1 $m^3$ ) of concrete

| Water/Cement Ratio | Cement (kg/$m^3$) | Sand (kg/$m^3$) | Gravel (kg/$m^3$) | Water (kg/$m^3$) |
|---|---|---|---|---|
| 0.5 | 380 | 565 | 1130 | 190 |

## Mixing , Casting and Curing :

All batches were mixed in a concrete mixer of (0.1 $m^3$) capacity .The inside surface of the mixer was moistened prior to use. The steel moulds were cleaned and oiled lightly before placing reinforcement. Steel reinforcement were placed in the mould and supported , as shown in **Fig. 2**. After mixing , concrete was poured into the moulds in two layers, each layer was compacted by hand using a steel rod. When a good compaction was attained , the surface of the specimen was leveled by steel trowel. After casting , specimens were left for 24 hours in the laboratory covered by polythene sheet, later , the moulds were removed carefully then, the specimens were marked and soaked in water for 28 days in the laboratory .

All specimens were painted white before testing so that cracks would be easily noticed .In order to determine the compressive strength of the specimens , three ( 150 x 300 mm ) concrete cylinders were taken from each batch according to the procedure of section C39/C39M-05 of the ASTM (2006 ) [3]. The compressive strength at (28) days age of the tested cylinders are shown in **Table 5** .

Table 5: Compressive strength of the tested cylinders

| Batch No. | Slab Symbol | Average compressive strength ( for three cylinders ) MPa at age of 28 days | Density ( $kN/m^3$) |
|---|---|---|---|
| 1 | S11 , S21 | 23.2 | 23.71 |
| 2 | S31 | 25.6 | 24.04 |
| 3 | D12 , D22 | 24 | 23.88 |
| 4 | D32 | 24.8 | 24.17 |
| 5 | D13 , D23 | 26 | 24.26 |
| 6 | D33 | 26.4 | 24.64 |
| 7 | D14 , D24 | 25.6 | 24.17 |
| 8 | D34 | 22.4 | 23.59 |
| 9 | D15 , D25 | 24.8 | 23.95 |
| 10 | D35 | 26.4 | 24.80 |

## Impact Test Rig :

The test rig was specially designed and constructed so that it could be used for the drop-weight impact tests for different dimensions of slabs and different impact forces implemented in the study .

The test rig consists mainly of two parts as described hereafter ( see **Fig. 3** ):-

1- Main supporting frame .
2- Vertical guide for the falling mass ( steel ball ).

The main supporting frame is a three dimensional structure consists mainly of steel members which are hollow square section ( 50 x 50 x 3 mm), jointed up together so as to provide a horizontal platform to provide both simple support or clamped support to the slab specimens. The platform is adjustable in spans in both directions by means of perforation of sides of the steel hollow box sections which fit other holes of cleat angles which are welded to the members in the other direction .

Supporting columns are ( 16 ) steel members of hollow square sections (50 x 50 x 3 mm) . These columns are , in turn , supported by means of four steel members of the same type braced together in both directions to avoid skewing which might cause eccentric loading or reactions .

The vertical guide is also composed of two parts, a perforated hollow tube member of ( 100 mm ) diameter. This tube is placed vertically to provide means of guidance on the top surface of the tested specimens. The vertical tube is supported and kept in position by means of a three dimensional frame of (2500 mm) height and ( 1060 mm) width . All members are steel hollow square sections of ( 38 mm ) size.

The striking object used is a ( 90 mm ) diameter steel ball of ( 3 kg ) mass with adjustable height ranging from ( 200 mm ) to ( 2000 mm ) . The steel ball is allowed to fall freely , thus , striking the top surface of the tested specimens at any desired position.

## EXPERIMENTAL PROCEDURE :

### Static Test Procedure :

One specimen in each group was tested under static loading .The static tests have been carried out using a compressive testing machine (at the structural laboratory in Kufa University), as shown in **Fig. 4**. Some changes have been made to the testing machine so that it could be used for static tests for different dimensions of slabs, such as using a steel supporting frame, as shown in **Fig. 5**.

After the specimen is fixed into position , a concentrated load was applied at the center of the specimen . The load was increased gradually at increments of ( 2 kN ) until failure . At each load increment, the central deflection was measured using a dial gauge fixed on a special holder beneath the specimen.

The failure mode and crack patterns were noticed and recorded .

### Impact Test Procedure :

A repeated impact drop-weight test with an increasing drop-height was adopted as a dynamic test procedure implemented in the present work . The falling mass (steel ball ) is ( 3 kg ) in weight and of ( 90 mm ) diameter for all impact tests.

Four Specimens in each group were tested under Impact loading . The impact test conditions for each specimen were given in **Table 1** . After specimen had been fixed into position , as shown in **Fig. 6** , the steel ball was lifted by hand to the specific height and then released (freely) to fall at the center of the tested slab .The ball was then raised up after impact , lifting and releasing the steel ball was then repeated for larger heights until the reinforced concrete slab starts to crack and then the cracks become wide enough to be visible .For each impact test , the maximum transient and residual central deflections were measured using linear variable differential transformer ( LVDT ) and crack patterns were noticed. The (LVDT) was calibrated prior to use it in the impact tests. Two LVDTs were fixed on a magnetic holder beneath the center and quarter points of the tested slab .

## EXPERIMENTAL RESULTS :

### Static Results :

A brief description of the load –deflection and cracking history of each tested slab is shown in **Table 6**.

Table 6 : Static results of the tested slabs

| Slab Symbol | Slab Dimensions ( mm ) | Reinf. Ratio % | First Cracking Load (kN) | Ultimate Load ( kN ) | Max. Central Defl. ( mm ) | First Cracking Load / Ultimate load ( %) |
|---|---|---|---|---|---|---|
| S11 | 1000 x 600 x 50 | 1.18 | 12 | 58 | 18.54 | 20.69 |
| S21 | 1000 x 1000 x 50 | 1.18 | 8 | 48 | 28.82 | 16.67 |
| S31 | 1000 x 1400 x 50 | 1.18 | 6 | 42 | 31.78 | 14.29 |

The load-deflection curves for the three tested slabs under static loads are shown in **Fig. 7.**

These curves for the tested slabs can demonstrate a certain tendency in which : at early stages of loading ; slabs behave elastically with no visible cracks which explains the behavior of slab before the first cracking load . At further stage, slabs tend to shift from elastic behavior and become rather to posses a nonlinear behavior with visible minor tension cracks beyond which ( at the third stage ) yielding occurs and the slabs behave plastically.

Test results demonstrated that the ultimate load becomes smaller as the slab dimensions increase , meanwhile , the central deflection of the slabs increase as the slab dimensions increase as shown in **Fig. 7**.The crack patterns at the bottom face of each tested slab are shown in **Fig. 8** .

### Impact Results :

Several selected slabs were dynamically tested under repeated impact with increasing the fall height of the striking object .

A steel ball of ( 90 mm ) diameter and (3 kg) weight was used as a falling load as planned for the impact tests .

In each impact test, the maximum transient and residual deflections at the center and quarter points of the slabs were recorded using two ( LVDT ) and digital video camera, as shown in **Fig. 9**.

The impact test results and some crack patterns for the tested slabs are given in **Figs.(10** to **24**).A complete examination of the test results which are given in the mentioned graphs reveals the following notes :

1. As a common fact , the central and quarter point deflections of each tested slabs tend to become larger as the falling height of the striker increases . The note is that , the deflections are directly proportional to the falling height at relatively low ranges of falls ( 600 – 800 mm ) , as the height of fall becomes larger , the rate of increase of deflections increases more significantly ( at an exponential relation with the height of fall ). Such a tendency might be related to the nonlinear behavior of the concrete specimens which occurs due to both sub yielding of reinforcing steel , tension cracking , crushing , and scabbing of concrete .

2. The second note is that the proportional limit ( the height of fall beyond which the fall-deflection curve becomes nonlinear ) seems to be slightly affected by changing ( increasing ) the slab dimensions . As an example , up to height of fall of (800 mm ) , the fall-deflection curve is linear in case of a slab of ( 1000 x 600 x 50 mm ) dimensions while the fall is only ( 700 mm ) for the case of a slab of ( 1000 x 1400 x 50 mm ) dimensions .
   This means that crushing and scabbing are rather affected by slab thickness rather than slab dimensions which at the same time have the major role in the nonlinear behavior of the tested specimens .
3. The proportional limit ( magnitude of height of fall beyond which nonlinearity is encountered ) is not affected greatly by increasing the reinforcement ratio at the tension zone . This means that concrete crushing and scabbing dominate the causes of nonlinear behavior of slabs under impact loading .
4. However , the central deflections of the tested slabs at failure stage of impact were proved to be smaller at higher percentages of the tensile reinforcing steel ratios for given dimensions of a slab and meanwhile , the central deflection of the slab at failure stage of impact becomes larger as the slab dimensions are increased .
5. Finally , it was found that , with the repetition of strikes and as the falling height of the striking object increases , cracks at the bottom faces of all slabs starts prior to those at the top face . These cracks tend to have random shapes and directions irrespective of dimensions of slabs . However , cracks do not propagate longitudinally or widen with the increase of heights of falls but rather scabbing of the concrete starts to form with large pieces of concrete scabbs out at larger drop height .

Such a behavior is related to the tendency of axial wave which travels across the thickness of the slab and reflects at the free end ( in fact the lower surface is considered as a free end ) thus, developing tensile stresses which are doubled in magnitude after reflection .

At the same time , the top face of the slabs acts as a fixed end with respect to the wave reflecting at this face just beneath the place of the falling mass which is kept stationary at the top face of concrete . Such an action results in double compressive stresses which in turn causes spalling of concrete at the top face of the slab .

## CONCLUSIONS :

Based on the experimental results obtained in the present study , several conclusions may be drawn and can summarized as follows :

1. The ultimate load of the tested slabs under concentrated static loads decreased with in a range of (17.2 – 27.5 % ) as the span of the slab increases by ( 60 – 125 % ) , meanwhile , the first crack load of the slabs decreases by ( 33 – 50 %) as the span of the plate increases by ( 60 – 125 % ) . Also, the actual central deflections of the tested slabs were found to be larger in magnitudes by ( 55 – 71.4 % ) as the span of the slab increases by ( 60 – 125 % ) .
2. The central deflections of the tested slabs under impact loads as obtained experimentally , tend to become larger as the falling height of the striker increases . Those deflections are directly proportional to the falling height at relatively low ranges of falls ( 600 – 800 mm ) , as the height of fall becomes larger , the rate of increase of deflections increases more significantly (at an exponential relation with the height of fall ).
3. The central deflections of the tested slabs under impact, as obtained experimentally were found to become smaller as the tensile reinforcing steel ratio increases , but the rate of the decrease in the dynamic deflection is small for high steel reinforcement ratio ( 1.77 % ) , meanwhile , the actual central deflection of the slabs becomes larger by ( 20 – 45 % ) as the span of the slab increases by ( 60 – 125 % ) .
4. The dynamic deflections of slabs with simply supported condition is larger than those deflections for slabs with clamped supports by a range of ( 45-70 % ) for the tested specimens.

5. Crack patterns at the bottom surface of the tested slabs under impact loads were found to be of a similar distribution in all slabs which have the same dimensions in spite of the difference in steel reinforcement ratio.
6. Scabbing of the concrete starts to form with large pieces of concrete scabbs out at larger drop height .

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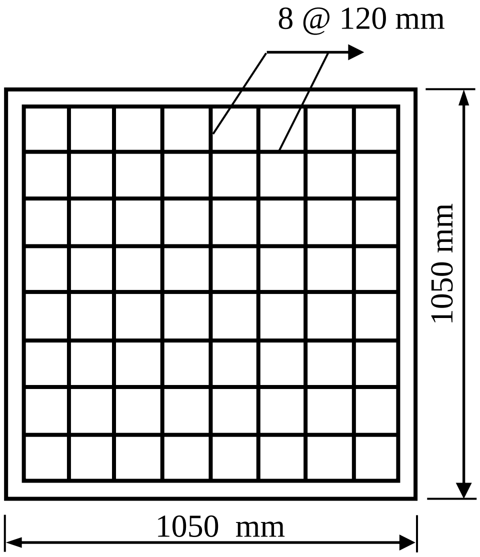



Fig.1 : Typical steel reinforcement of a test specimen

Fig 2 : Arrangement of steel reinforcement bars in the mould before casting.

Fig.3 : Impact test rig

Fig. 4: Compressive testing machine

Fig. 5: The static test arrangement

(a) Simply supported

(b) Clamped supported

Fig.6 : Impact test arrangement

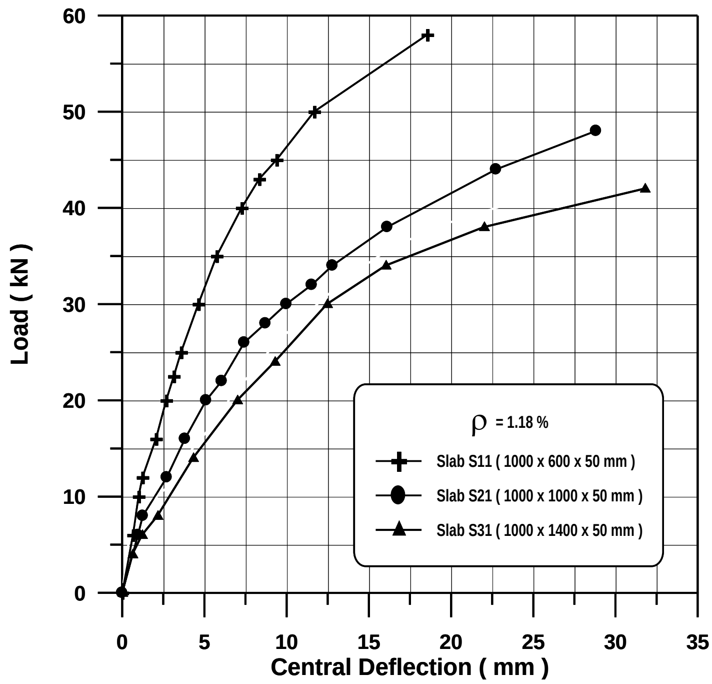
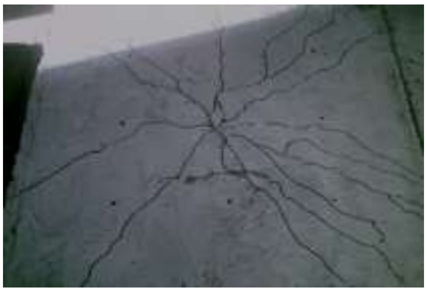



Fig. 7: Load – deflection curves for different dimensions of slabs

(a) Slab S11



(b) Slab S21

(c) Slab S31

Fig.8 : Crack patterns of static test of slabs ( S11,S21 and S31)

Fig. 9 : Impact test measurement

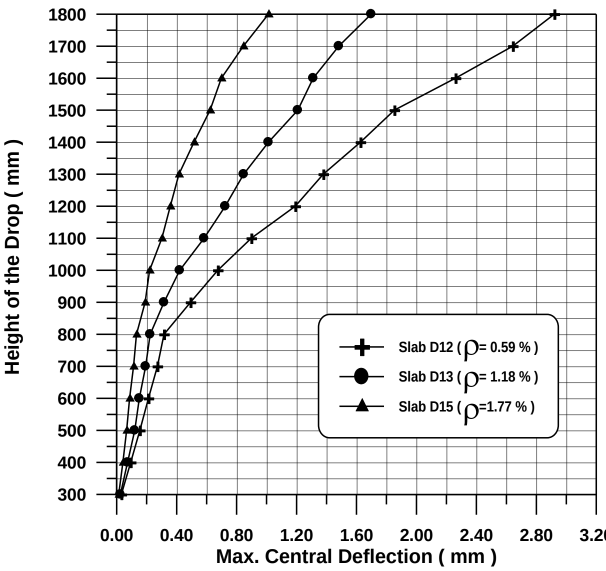



Fig.10: Effect of height of impact on dynamic deflection for different steel reinforcement ratios ( ρ ) for slab of dimensions (1000 × 600 × 50 mm )

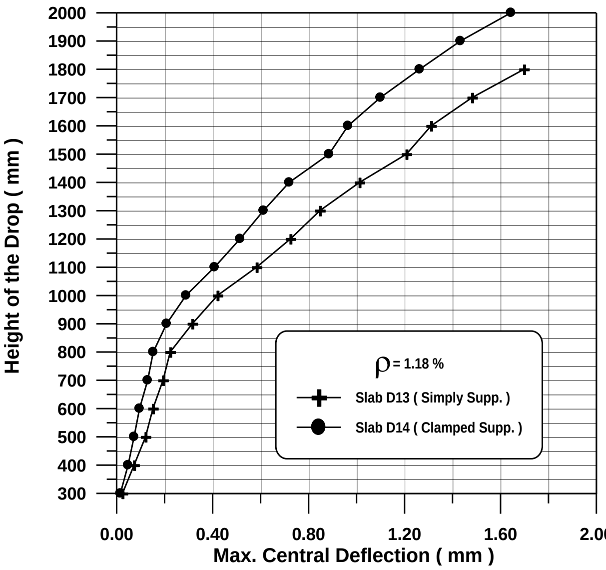



Fig.11: Effect of height of impact on dynamic deflection for different support conditions for slab of dimensions (1000 × 600 × 50 mm )

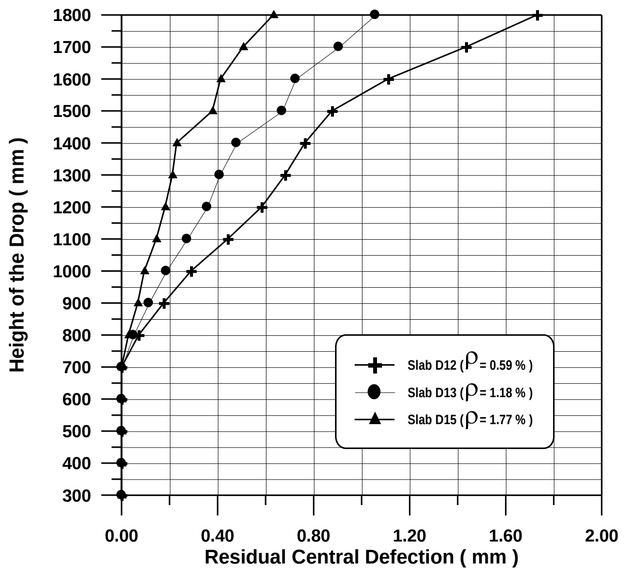



Fig.12: Effect of height of impact on residual dynamic deflection for different steel reinforcement ratios for slab of dimensions (1000 × 600 × 50 mm )

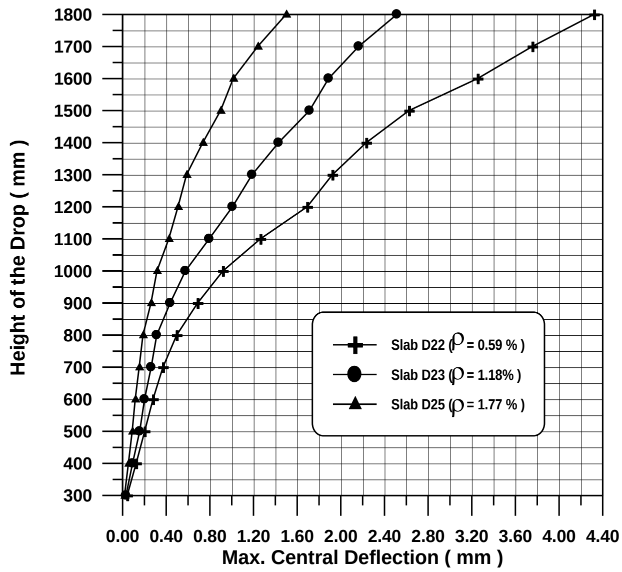



Fig.13: Effect of height of impact on dynamic deflection for different steel reinforcement ratios for slab of dimensions (1000 × 1000 × 50 mm )

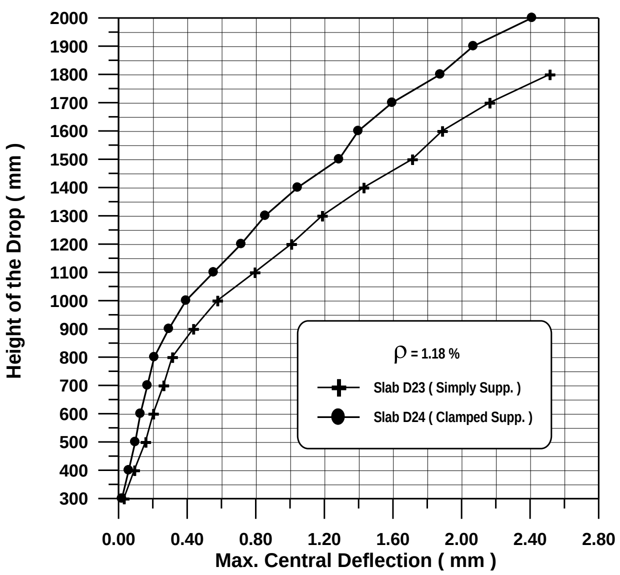



Fig.14 : Effect of height of impact on dynamic deflection for different support conditions for slab of dimensions (1000 × 1000 × 50 mm )

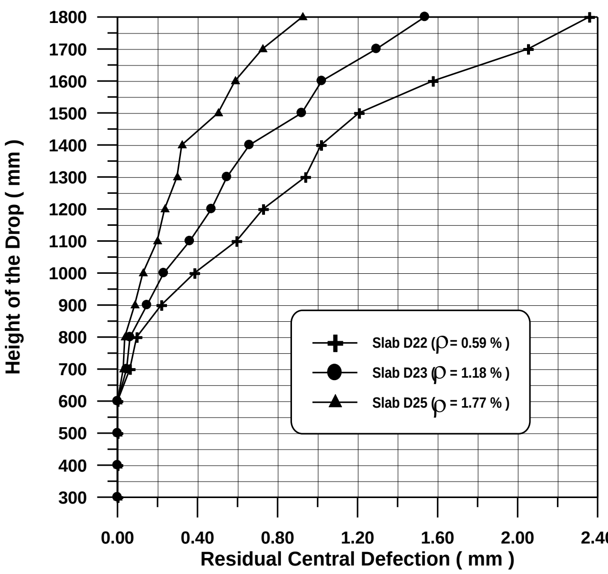



Fig. 15 : Effect of height of impact on residual dynamic deflection for different steel reinforcement ratios for slab of dimensions (1000 × 1000 × 50 mm )

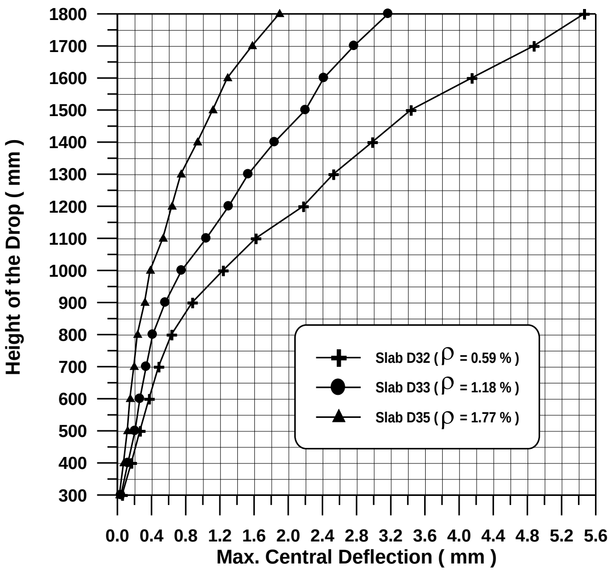



Fig.16: Effect of height of impact on dynamic deflection for different steel reinforcement ratios for slab of dimensions (1000 × 1400 × 50 mm )

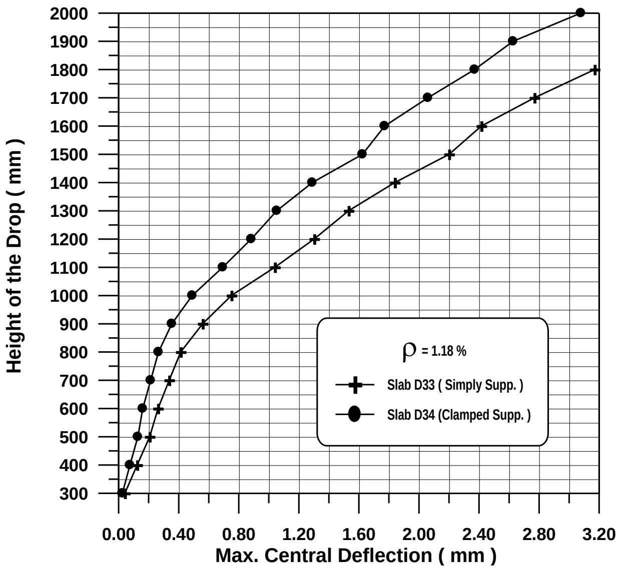



Fig.17: Effect of height of impact on dynamic deflection for different conditions for slab of dimensions (1000 × 1400 × 50 mm )

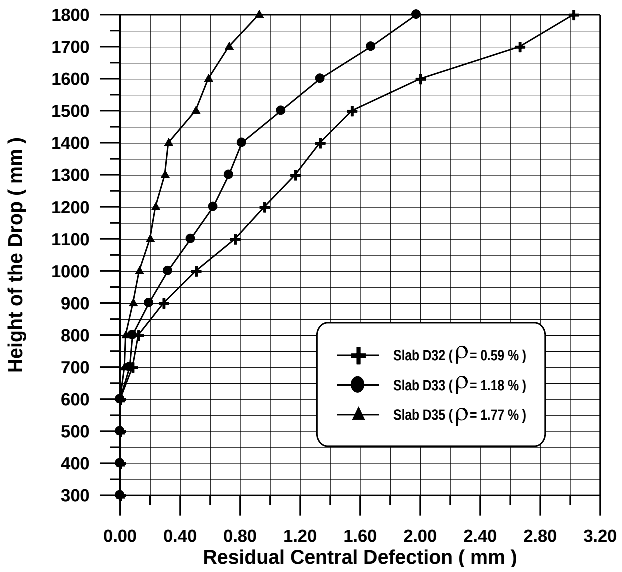



Fig.18: Effect of height of impact on residual dynamic deflection for different steel reinforcement ratios for slab of dimensions (1000 × 1400 × 50 mm ).

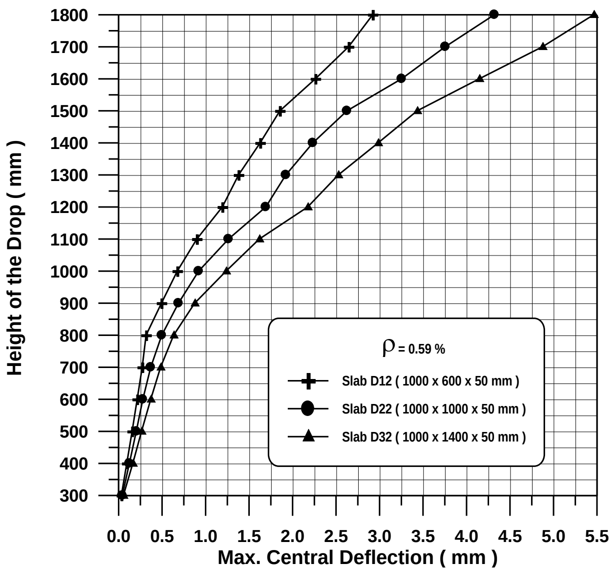



Fig.19: Effect of height of impact on dynamic deflection for different dimensions of slabs with steel reinforcement ratio ( ρ= 0.59 ) .

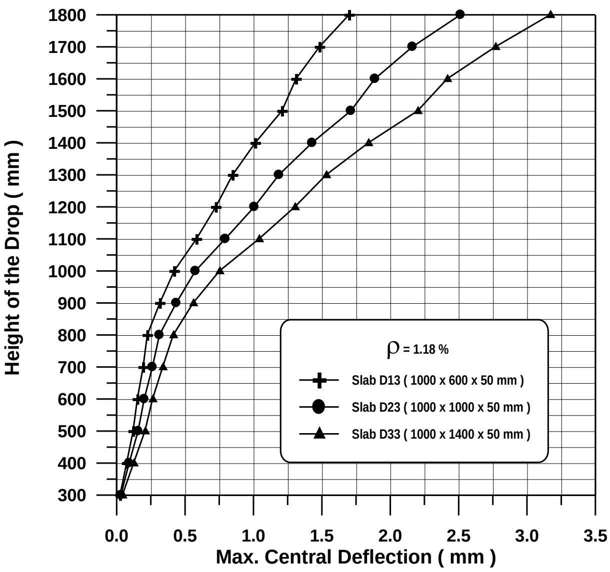



Fig.20 : Effect of height of impact on dynamic deflection for different dimensions of slabs with steel reinforcement ratio ( ρ= 1.18 % ) .

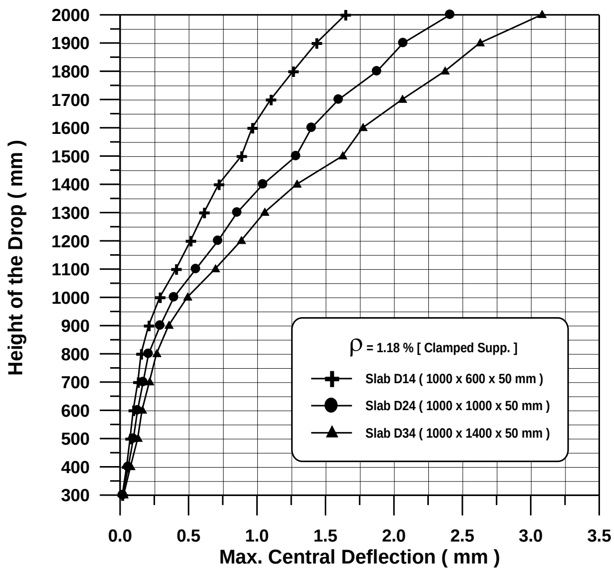



Fig.21: Effect of height of impact on deflection for different dimensions of slabs (clamped supp.) with steel reinforcement ratio ( ρ= 1.18 % ) .

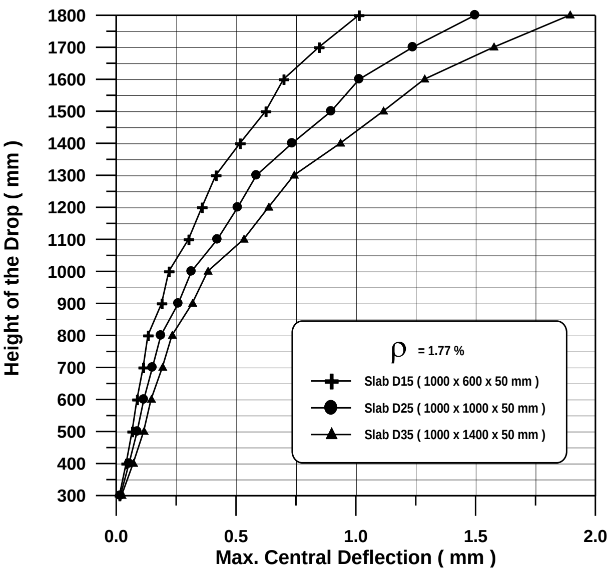



Fig.22: Effect of height of impact on dynamic deflection for different dimensions of slabs with steel reinforcement ratio ( ρ= 1.77 % ) .



( a ) Top face


( b ) Bottom face

Fig.23: Crack patterns and local failure mode of slab (D13) under impact loading (1000 × 600 × 50 mm; ρ = 1.18 % ; simply supported; falling height = 1.8 m )


( a ) Top face

( b) Bottom face

Fig. 24 : Crack patterns and local failure mode of slab (D14) under impact loading (1000 × 600 × 50 mm; ρ = 1.18 % ;clamped supported ; falling height = 2 m )