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Drop-weight impact tests on reinforced concrete beams

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Abstract

This master’s thesis aimed to investigate the behaviour of reinforced concrete beams under dynamic loading conditions, specifically focusing on understanding shear failure. The study was conducted with KTH Royal Institute of Technology, the Swedish Fortifications Agency, and Tyréns. The research built upon previous studies and aimed to contribute to understanding dynamically loaded concrete structures.

The thesis included a literature study to explore the fundamental concepts of dynamics, impulse loading, and the response of RC structures under dynamic and static loading. The experimental part involved manufacturing and testing 27 reinforced concrete (RC) beams with varying amounts of transverse reinforcement and load positions, where 18 were tested dynamically, and the rest were tested statically. The findings contribute to understanding structural response and failure mechanisms in such beams, considering three main factors: load position, shear reinforcement, and loading characteristics. In addition, essential data, such as reaction forces, beam displacements, and crack patterns, were measured using load cells, accelerometers, and high-speed cameras.

The findings of the study revealed several important insights. The load’s position significantly affected the beams’ acceleration, with further load positions activating both shear and flexural modes simultaneously. Beams with different shear reinforcement configurations exhibited similar behaviour and the presence of weaker cross-sections due to insufficient bonding between steel and concrete. The study also demonstrated that dynamic loading increased the beams’ load capacity compared to static loading, attributed to the strain rate effect and inertia forces. The crack patterns and residual eigenfrequency differed between dynamic and static loading conditions, with dynamic loading resulting in less extensive cracking and reduced residual stiffness.

The use of a fiberboard provided cushioning effects, as its removal during testing resulted in a shortened load duration and the formation of cracks in the beams. In addition, anchoring the flexural reinforcement significantly increased the stiffness of the beams, leading to an earlier rebound and a more robust impact response.

Keywords: Reinforced concrete beams, dynamic loading, shear failure, shear reinforcement configuration, load position, strain rate effect, impulse loading.
Sammanfattning

Detta master examensarbete syftade till att undersöka beteendet hos armerade betongbalkar under dynamiska belastningsförhållanden med fokus på att förstå skjuvbrott. Studien genomfördes i samarbete med KTH Kungliga Tekniska Högskolan, Fortifikationsverket och Tyréns. Forskningen byggde på tidigare studier och syftade till att bidra till förståelsen av beteendet hos betongstrukturer som belastas dynamiskt.

Arbetet inkluderade en litteraturstudie för att utforska de grundläggande koncepten inom dynamik, impulsbelastning och responser hos armerade betongstrukturer under dynamisk och statisk belastning. Den experimentella delen innehållde tillverkning och provning av 27 armerade betongbalkar med varierande mängd skjuvarmering och belastningspositioner, där 18 testades dynamiskt och resten testades statiskt. Resultaten bidrar till förståelsen av strukturell respons och brottmekanismer hos sådana balkar och tar hänsyn till tre huvudsakliga faktorer: belastningsposition, skjuvarmering och belastningskarakter. Viktiga data som reaktionskrafter, balkens förskjutningar och sprickmönster mättes med hjälp av lastceller, accelerometrar och höghastighetskamera.


Användningen av en träfiberskiva gav en dämpningseffekt, då dess borttagning under testningen resulterade i kortare varaktighet och bildning av mer sprickor i balkarna. Förankring av böjarmering ökade signifikant balkarnas styvhet, vilket ledde till en tidigare återfärding och en styvare respons.

Nytteland: Armerade betongbalkar, dynamisk belastning, skjuvbrott, skjuvarmering konfiguration, belastningsposition, töjningshastighet, impulsbelastning.
Preface

This experimental study constituted an essential component of our Master’s Degree program. It was carried out at the Department of Civil and Architectural Engineering, Division of Concrete Structures at KTH, in collaboration with Tyréns. Without the invaluable help and support of the individuals involved, conducting this work would have been impossible.

First and foremost, we are deeply grateful to our examiner, Prof. Anders Ansell, whose guidance and support were instrumental in completing this thesis. We sincerely appreciate your constructive opinions and assistance.

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Furthermore, we thank the lab managers, Viktor Brolund and Gürsel Hakan Taylan, for their exceptional assistance during the experimental procedures. Your support and resourceful solutions were indispensable to the success of this study.

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A special thanks go to our families and friends who have provided us with support and encouragement. Your belief in us has been a constant source of motivation and strength.

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Chapter 1

Introduction

1.1 Background

Concrete is a widely used building material for constructing large buildings, and it is crucial to comprehend its behaviour under different loading conditions. The bearing capacity of concrete structures is determined by their flexural and shear strength capacities, with the former typically being designed to be greater than the latter. The flexural failure mode is considered a safe ductile mode, providing early warnings before failure, such as wide cracks. Furthermore, ductile failure modes are desirable under impulsive loads due to their larger energy absorption capacity. In contrast, shear failure modes are brittle and occur suddenly without any warning signs. Minimizing the risk of failure in concrete structures is of utmost importance to prevent severe consequences such as human injuries or costly repairs. While there is abundant research on various types of failures of concrete structures subjected to static loads, the response to impulsive loads still needs to be fully understood and requires further research. The discrepancy between the response under dynamic and static loads is due to wave propagation effects (Cotsovos et al., 2008) and inertia forces (Saatci and Vecchio, 2009).

The main objective of this master’s thesis is to contribute to ongoing research on dynamically loaded concrete structures in collaboration with Chalmers University, The Swedish Fortifications Agency, KTH Royal Institute of Technology, MSB, The Swedish Civil Contingencies Agency and Swedish Transport Administration (Trafikverket). Furthermore, this project aims to build on the knowledge and conclusions obtained from previous studies such as Atterling and Widmark (2022), Peterson et al. (2022), and Peterson and Ansell (2021).

1.2 Aims and scope

Previous studies have revealed that reinforced concrete (RC) beams, designed to fail in flexure under static loading, can experience shear failure under dynamic loading. This, although the elements were designed following the relevant design provisions to show a ductile failure mode. The different characteristics of static and dynamic loading can explain this difference between the anticipated and observed failure modes.
CHAPTER 1. INTRODUCTION

Specifically, dynamic loading results in inertia forces that give rise to different internal section forces, such as shear force and bending moment, which can change the failure mode. Therefore, the primary aim of this thesis is to investigate the behaviour of RC beams under dynamic loading conditions and to focus specifically on understanding the occurrence of shear failure. The specific aim of this thesis is to investigate the differences between static and dynamic loading, the effect of the transverse reinforcement spacing, and the effect of the load position.

1.3 Method

The first part of this thesis includes a literature study, which aims to increase the knowledge about the fundamental concepts of dynamics, impulse loading, and the response of RC structures under dynamic and static loading.

The second part describes the manufacturing and testing of the beams. All beams were cast with the same concrete mix and contained the same longitudinal reinforcement amount. During the dynamic tests, a 70 kg mass was dropped from a height of 2.4 m. The static loading was applied using an MTS machine. The tests were conducted with varying amounts of transverse reinforcement and load position.

Both test types were instrumented to measure essential results for the study. For the static tests, this included the force applied by the piston and the beam displacement at the piston. The dynamic tests were instrumented with load cells at the supports to measure the reaction forces. Also, accelerometers were used at the mid-point to determine this position’s acceleration, velocity and displacement. Finally, an additional accelerometer was placed on the mass to determine the contact force between the mass and the beam.

1.4 Limitations

This thesis project was limited to the study of simply supported RC beams. The tests were restricted to 27 beams, with 18 out of the 27 being tested dynamically and the rest tested statically. The varied parameters during the tests were limited to three main parameters: the loading position, the shear reinforcement content, and the loading characteristics. Two other interesting parameters were studied, which were the effect of removing the fiberboard and anchoring the flexural reinforcement.

Additionally, the static tests were limited to the maximum capacity of the MTS machine, which was incapable of withstanding any loads exceeding 150 kN.

1.5 Outline

This master thesis is divided into 7 chapters:

- Chapter 2 includes the basic principles which describe the dynamic response of the material with emphasis on beam response.
• **Chapter 3** describes the different failure mechanisms for reinforced concrete beams during static and dynamic loading.

• **Chapter 4** dissects the experimental procedure where the dynamic and static setups are illustrated.

• **Chapter 5** presents the results from conducted experiments by comparing different parameters.

• **Chapter 6** includes a discussion of the different parameters’ effect on the beams.

• **Chapter 7** summarizes the most valuable findings in this experimental study and introduces some suggestions for future research.
Chapter 2

Dynamic response of concrete beams

2.1 Fundamental dynamic theories

This chapter introduces the basics of structural dynamics for the study of dynamically loaded beams which are the topic for this thesis. The background summarized and described in this chapter is based on Johansson and Laine (2012).

External forces do work on systems and must be safely absorbed. The amount of work $W$ applied is equal to the product of the applied force $F$ and the displacement along a straight line caused by this force. This relation is explained by:

$$ W = \int F \, du $$ (2.1)

Furthermore, the external work $W_e$ due to the dynamic load can also be defined as the difference in the kinetic energy $E_k$ of the system before and after the force is applied:

$$ E_k = \frac{1}{2} \cdot (m \cdot v^2) $$ (2.2)

$$ W_e = E_{k1} - E_{k0} = \frac{1}{2}(m \cdot v_1^2) - \frac{1}{2}(m \cdot v_0^2) $$ (2.3)

where

$m$ = the mass [kg]
$v_0$ = the initial velocity [\( \text{m/s} \)]
$v_1$ = the velocity after exerted work [\( \text{m/s} \)]

According to the energy conservation, the external work $W_e$ needs to be balanced by an equivalent internal work $W_i$:

$$ W_i = W_e $$ (2.4)

The exerted force on the particles inside the system will lead to a change in the linear momentum of the particles. This change is also called impulse and relates to
CHAPTER 2. DYNAMIC RESPONSE OF CONCRETE BEAMS

the change of momentum as shown in Eq.(2.5). If the system has no velocity before the exerted velocity, the impulse can be further simplified as in Eq.(2.6):

\[ I = \Delta p = m \cdot v_1 - m \cdot v_0 = \int_{t_0}^{t_1} F(t) \, dt \]  

(2.5)

\[ I = m \cdot v_1 \]  

(2.6)

Furthermore, it is possible to describe the change of kinetic energy due to the impulse as:

\[ E_k = \frac{I^2}{2m} \]  

(2.7)

2.1.1 Impact load

To better understand the meaning of impact loading in the context of this study, there are two characteristic loading cases in dynamic loading that need to be understood, which are impulsive loads and long-period loads. The difference between these is the magnitude of the pressure and the duration. In the case of an idealized impulsive load, the pressure is infinitely high and exerted under an infinitely short duration, whereas during long-period loads, the pressure is exerted under a longer duration. This can be seen in Figure 2.1. Impact loads are often idealized as impulsive loads due to their relatively short duration.

![Figure 2.1](image)

Figure 2.1: The two ideal cases of dynamic loading. (a): idealized impulsive loads, (b): long-period loads.

In general, a dynamic load exerted upon a system show characteristics somewhere in between these two ideal cases. An impact load is very similar in nature to the case of an idealized impulse, as it has a very short duration with relatively large pressure. Thus for this study, the structural system will be assumed to be subjected to a characteristic impulse load \( I_k \) due to an impact.

2.1.2 The beam impact problem

A beam at rest with a mass \( m \) subjected to an impact from a striker is shown in Figure 2.2. The impact results in a relative deformation \( z \) between the striker and the beam due to contact zone deformation. The deformation cycle consists of two
2.1. FUNDAMENTAL DYNAMIC THEORIES

intervals: the approach interval and restitution, where the deformations increase in the approach interval and decrease in the restitution interval. The relation between the approach and restitution is determined by the elasticity and plasticity at the contact zone; see Figure 2.3 (Hughes et al., 1982). This can also be visualized by the simple collision model, which presents two different types of collision, elastic and plastic, see Figure 2.4. In a perfect plastic collision, the bodies will have the same velocity after the collision, while the colliding bodies will have different velocities in the perfect elastic collision case.

Figure 2.2: Impact zone in the beam.

Figure 2.3: Approach and restitution intervals. From Hughes et al. (1982)

Figure 2.4: Elastic and plastic cases after the collision. From Aphram and Mendoza (2017).
2.1.3 Soft and hard Impacts

In the tests carried out within this master thesis, the striker weighed 70 kg and was dropped from a height of 2.4 m on beams with different configurations of shear reinforcement. The collision between two bodies, one with initial velocity (the striker) and the other at rest (the beams), can be illustrated with a simplified mechanical model as in Figure 2.5. There are two different types of impact: where during a soft impact most of the deformation in the system occurs due to the response of the striker. During a hard impact, the response of the system is mainly due to the response of the beam. Both cases are depicted in Figure 2.6.

![Figure 2.5: Illustration of the simplified mechanical system for the collision between the striker and the beam. From CEB (1988).](image)

In the experiments presented in CEB (1988) after the striking mass hit the beam at the midspan, the mass starts to decelerate, and the beam moves downward until its velocity became zero, then the movement of the beam changes the opposite, upward, direction. The supports were observed to move upward as shown in Figure 2.7, where \( t_1 \) is before the striker hits the beam, \( t_2 \) when the striker impacts the beam, and \( t_3 \) when the beam response causes upward motion. Regarding the failure mode, it was observed that shear failure occurred before bending failure due to the cracks which developed suddenly after the striker impacted the beam. Further, the conclusion from the test experiments regarding the dominating failure mode during a short strong impact is shear failure (CEB, 1988).

![Figure 2.6: Soft and hard impact. From CEB (1988).](image)
2.2 Material response

This section summarizes the basics of the material behaviour and the response of the studied specimens. Reinforced concrete is a composition of the main materials of this study, concrete and steel. The material response will be simplified and divided into three categories: an elastic, a plastic, and an elastoplastic response.

2.2.1 Structural response

When a structure is subjected to an impulsive load, it gives rise to internal forces. These forces work against the load and restore the system to an undeformed shape, given that the structure is within its elastic range. These internal forces are seen as structural resistance, and their functions vary depending on different parameters, such as loading type and material properties (Jönsson and Stenseke, 2018).

Elastic response

The resistance $R_u$ mentioned above is in this type of response related to the deformation $u$ and the structural stiffness $k$ according to:

$$R(u) = k \cdot u$$  \hspace{1cm} (2.8)

The structural stiffness $k$ can be obtained from Figure 2.8, as it is the slope of the resistance. The elastic deformation $u_{el}$ is reversible, and the structure returns to its initial undeformed shape when unloaded.
Plastic response

Under perfect plastic response, the deformations are limited by internal resistance. The material in the structure will not show any deformation as long as the exerted force is less than the internal plastic resistance. However, when the force reaches the maximum plastic resistance $R_m$, the material will show deformation during loading. The plastic deformation $u_{pl}$ is non-reversible, and the structure cannot obtain its initial undeformed shape after unloading, see Figure 2.9a.

Elastoplastic response

Under the elastoplastic response, the material behaviour, as stated by the name, is a combination of elastic and plastic behaviours. This combination gives a more accurate presentation of the structural behaviour under loading. The material behaves elastically until the maximum resistance is reached, and thereafter the material begins to behave plastically.

As explained above, the behaviour of the material is divided into two parts, which is seen in the deformation as well. The first part of the deformation is elastic deformation, which is reversible, while the other part is plastic deformation which is non-reversible. This division of the deformation is demonstrated in Figure 2.9b.
The total deformation of the structure $u_{tot}$ can be calculated as the sum of the plastic deformation $u_{pl}$ and the elastic $u_{el}$.

$$u_{tot} = u_{pl} + u_{el}$$  \hspace{1cm} (2.9)

$$u_{el} = \frac{R_m}{k}$$  \hspace{1cm} (2.10)

### 2.2.2 Concrete

Concrete as a material is characterized by the difference between its high compressive and low tensile strengths. To overcome the tensile weakness of the concrete, steel reinforcement is used. Concrete is also known to have a non-linear behaviour of its stress-strain relation in both compression and tension. This can be seen in Figure 2.10 (Munther and Runebrant, 2018). Moreover, Figure 2.10 shows that the ultimate strain that the concrete obtains after reaching its maximum tensile strength is significantly lower than its counterpart under compression. Furthermore, the form of the curve indicates that the concrete exhibits a more brittle failure under tension compared to compression.

![Figure 2.10: The non-linear behaviour of the stress-strain relationship for concrete (Jönsson and Stenseke, 2018).](image)

The ductility of the failure under compression is for concrete dictated by the strength of the material. As shown in Figure 2.11, concrete with lower strength allows for more deformation after reaching maximum stress. In other words, concrete with high strength is more brittle compared to low-strength concrete, which is more ductile. The strain rate has an impact on the compressive strength of the concrete. This can be seen in Figure 2.12, which illustrates that the ultimate strain increases with the compressive strength. In other words, concrete exhibits higher stiffness under high strain rates (Jönsson and Stenseke, 2018).
2.2.3 Reinforcement steel

Steel is commonly used in combination with concrete to compensate for the relatively low tensile strength. Reinforcement steel is categorized into two different categories depending on the production procedure. The categories are hot rolled and cold worked. The main difference between these two can be seen in their stress-strain relations. Figure 2.13 shows these relations, $f_u$ is the maximum tensile strength, $f_y$ the yield strength and $\varepsilon_u$ the ultimate strain (Munther and Runebrant, 2018).

The tensile behaviour of hot-rolled steel can be divided into four distinct stages, the elastic stage, the plastic stage (yield plateau), strain hardening up to maximum tensile stress, and a fracture stage leading to failure. In contrast, cold-worked steel undergoes three different stages consisting of the elastic stage, strain hardening, and fracture stage. However, the yield limit of cold-worked steel is not as clearly

Figure 2.11: An illustration of the increased brittleness of the concrete with increased compressive strength (Jönsson and Stenseke, 2018).

Figure 2.12: Increase of concrete strength and stiffness with strain rate (Jönsson and Stenseke, 2018).
defined as that of hot-rolled steel. According to the Eurocode (CEN, 2006), the stress results in a remaining strain of 0.2% after unloading can be termed as proof stress $f_{0.2}$, which is also defined as yield strength. From Figure 2.13, it can be seen that hot-rolled steel generally exhibits a higher ultimate strain and strain hardening, leading to more ductile behaviour.

![Stress-strain relations for (a) Hot rolled steel and (b) Cold worked steel (CEN, 2004).](image)

The classification of reinforcement steel is done regarding various parameters, e.g. strength, size, ductility, etc. The capacity of the steel to deform during tension, also known as ductility, is of great importance for this study. There are three classes of ductility according to the Eurocode (CEN, 2004). Steel is divided into these classes with regard to the relation between its maximum strength and yield strength and also to its ultimate strain. The three classes are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Class</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{yk, f_{0.2}}$ [MPa]</td>
<td>400-600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum value of $\frac{f_{uk}}{f_y}$</td>
<td>$\geq 1.05$</td>
<td>$\geq 1.08$</td>
<td>$\geq 1.15 &amp; &lt;1.35$</td>
</tr>
<tr>
<td>Ultimate strain $\varepsilon_{uk}$ [%]</td>
<td>$\geq 2.5$</td>
<td>$\geq 5$</td>
<td>$\geq 7.5$</td>
</tr>
</tbody>
</table>

2.2.4 Reinforced concrete

Combining concrete and steel creates a composite material with the high compressive strength of the concrete and with high ductility and tensile strength of the steel. This material is known as reinforced concrete (RC) and is widely used in many types...
of structures. A simply supported RC beam is one example of how to use RC and is the main subject of this thesis.

RC elements behave somewhat differently compared to their original materials, i.e. concrete and steel, and are affected by a load exhibit a relation between loading and displacement, which can be divided into three stages, as seen in Figure 2.14. The concrete is assumed to be uncracked and to have a linear elastic response throughout the duration of state I. The stiffness of an RC element during this state is governed by the stiffness of the concrete, even though the steel can have an effect that could increase the stiffness by almost 20%, but this contribution is usually ignored (Munther and Runebrant, 2018).

When the RC element enters state II, the concrete cracks, but the reinforcement steel has yet to reach its yield limit. The stiffness in state II depends on both the concrete and the steel and is significantly lower than that during state I. Then, State III is initiated after State II when the reinforcement steel has reached its yield limit. When this occurs, the RC element will start to lose its stiffness rapidly. Reaching this state does not necessarily means that the RC element will fail or collapse, as a plastic redistribution of stresses will occur, and the failure will not be reached unless either the concrete or the steel has reached its ultimate strain. The shear failure is more brittle than the flexural failure due to the fact that concrete does not possess a significant plastic deformation capability in shear.

2.2.5 Strain rate effect

When a material is loaded dynamically, the acceleration that is introduced into the system may lead to significant inertia forces, which increase the strength (Cotsovos, 2010). This effect is commonly known as the strain rate effect and should be understood as a strength increase relative to the change of strain over time, which has
The strain rate effect results in an increase in the strength of some materials, which affects the structural response of the element. An RC element subjected to a dynamic load will deform during a short time period, and the strain rate in the concrete and steel will be significantly higher than in the case of a static load. As a comparison, a static load for concrete results in strain rates between $10^{-5}$ and $10^{-6}$ while an impact load results in strain rates of approximately $10^{0}$ (Magnusson, 2019).

The phenomenon of increased material strength under dynamic loading is normally considered in a simplified way by utilizing dynamic increase factor and is denoted $DIF$, which is the relation between the dynamic strength $F_{dyn}$ and the static strength $F_{sta}$:

$$DIF = \frac{F_{dyn}}{F_{sta}}$$

(2.11)
Chapter 3  
Shear failure of reinforced concrete beams

The objective of this chapter is to explain the different behaviours of RC beams under static and dynamic loads, with a focus on the specific types of shear failures that may occur in each case. Furthermore, the underlying mechanisms responsible for each failure mode will be clarified. Specifically, static loading can induce four distinct types of shear failures: direct shear failure, crushing of concrete struts, shear failure by shear compression, and flexural shear failure.

3.1 Shear failure during static loads

When subjected to static loads, concrete beams resist shear through two distinct mechanisms: beam action and arch action. For beam action, a part of the shear force is transferred through the compression zone, while the remainder is carried through interlocking and friction from the aggregates, the transverse shear and moment of the concrete cantilevers between two cracks, dowel action, and tension in the flexural reinforcement. Beam action assumes that the bond between the concrete and the reinforcement is perfect (Magnusson, 2019).

Regarding arch action, the development of horizontal forces at the supports and through the flexural reinforcement, and its anchorage, play a critical role. In real concrete beams, the slip effect prevents perfect bonding between the concrete and reinforcement during the cracking process. As shear cracks start to develop, beam action gradually transitions into arch action, which ultimately leads to the failure of the beam when both mechanisms are unable to transfer the shear forces. It is worth noting that the load capacity of the structure is likely to be higher if a fully developed arch action is achieved (Magnusson, 2019).

3.1.1 Direct shear failure

If the shear forces near the supports are significant, direct shear failure can develop throughout the depth of the beam. The nature of direct shear failure differs between cracked and uncracked beams. In the case of cracked beams, shear failure will occur along the plane of the crack and will resemble shear-friction, where the transfer
of shear occurs through frictional resistance to sliding between the surfaces along the crack plane. In contrast, in uncracked beams, the transfer of shear is achieved through a combination of shear and compression of the struts, resulting in a chain of diagonal tension cracks along the shear plane. Figure 3.1 provides an illustration of both scenarios (Ross, 1983).

![Figure 3.1: Shear transfer in cracked and uncracked beams. From Ross (1983).](image)

Figure 3.1: Shear transfer in cracked and uncracked beams. From Ross (1983).

In accordance with Magnusson (2019), direct shear failure is unlikely to occur due to distributed load, and therefore, the direct shear failure will occur when the load is a point load placed close to the support, with shear slenderness $\frac{a}{d} < 0.5$, where $a$ is the shear span and $d$ is the effective depth. Direct shear failure, shown in Figure 3.3a, occurs when local shear stresses exceed the ultimate capacity of the concrete struts at the ends or by the failure of compression struts resulting from the combined effects of shear and compression, see Figure 3.2 for illustration of compression strut.

### 3.1.2 Failure caused by crushed or split compressive strut

This type of failure involves the inclined concrete compressive struts, shown in Figure 3.2, at each support carrying a portion of the load, and failure occurs when these struts are crushed or split. This failure mode is more likely to occur under point loads rather than distributed loads, where shear slenderness is $0.5 < \frac{a}{d} < 1.5$ for point loads and $\frac{a}{d} < 5$ for distributed loads (Magnusson, 2019). See Figure 3.3b.
3.1.3 Shear failure by shear compression

In regions of a beam where the bending moment is relatively low and the shear force is relatively high, diagonal tension cracks may develop. These cracks do not initially arise from flexural cracks and may be accompanied by web shear cracks in the affected region of the beam, as illustrated in Figure 3.3c. As the load increases, these cracks propagate, resulting in a continuously decreasing compression zone until the elements are crushed by the high compressive stresses, as shown in Figure 3.3d. This type of failure is known as shear compression and its shear slenderness requirements for a point-loaded beam are $\frac{a}{d} \geq 1.5$ and $\frac{a}{d} \leq 3$, while for a distributed-loaded beam, the requirements are $5 \leq \frac{L}{d} \leq 11$, as stated by Magnusson (2019).

3.1.4 Flexural shear failure

The flexural cracks start propagating when the principal tensile stresses exceed the concrete’s tensile strength. This occurs in regions where the moments are larger than the cracking moments. However, in the regions where the shear forces also are high, there will be a combined action of shear and tensile stresses and this combination will generate diagonal tensile cracks (Park and Paulay, 1974). This shear failure type can occur in beams loaded by distributed load and point load, where the shear slenderness under condition point load and distributed load is $3 \leq \frac{a}{d} \leq 7$ and $11 \leq \frac{L}{d} \leq 20$, respectively (Magnusson, 2019). see Figure 3.3e.

![Figure 3.3: Different types of static shear failure. From Magnusson (2019)](image)
CHAPTER 3. SHEAR FAILURE OF REINFORCED CONCRETE BEAMS

3.2 Shear failure during dynamic loads

The behaviour of reinforced concrete structures differs between static and dynamic loads. The distribution of shear forces and bending moments vary between the two loading conditions due to the acceleration of the structural elements under dynamic loads. Therefore, the effects of kinetic energy and inertia must be considered when analyzing structures dynamically. Furthermore, studies have shown that structures subjected to impulsive loads tend to fail in shear (Magnusson, 2019).

In this section, two main types of dynamic shear failure will be discussed, where the first failure type is a direct shear failure, and the second type is a flexural shear failure.

3.2.1 Direct shear failure

Direct shear failure can occur under dynamic loading even if the load is distributed, for example, as a blast load. In a study by Slawson (1984), where a slab on two vertical walls was subjected to dynamic load, it was found that no flexural deformation occurred in the middle part of the slab, but direct shear failure occurred at the supports (the connection between slab and walls), see Figure 3.4. Due to the lack of knowledge about the actual process of direct shear failure during dynamic loading conditions, it was stated by Magnusson et al. (2014) that direct shear failure starts as vertical cracks that rapidly propagate through the depth of the beam.

![Figure 3.4: Illustration of the direct shear failure case by Slawson (1984). From Magnusson (2019).](image)

3.2.2 Flexural shear failure

Experiments and numerical simulations have been performed to study flexural shear failure during impulsive loads. In the investigation conducted by Magnusson and Hallgren (2000), it was found that beams which under static loads showed ductile flexural failure, instead showed brittle shear failure modes under impulsive loads. Magnusson (2019) also highlighted the importance of the reinforcement content which constitutes an essential factor to determine the stiffness of the beam, where stiffer beams are more likely to fail in shear while less stiff are more prone to fail in bending.
Chapter 4

Experimental procedure

4.1 Overview

In this experimental study, a total of 34 beams were cast and subjected to various loading conditions. These beams were constructed with varying amounts of shear reinforcement and the spacing varied but with the same stirrup diameter, which was 6 mm. Due to the size limitations of the concrete mixer used, the beams were cast in batches of two. With each batch of beams, a concrete cube was cast, resulting in a total of 16 cubes that were used to determine the compressive strength of the concrete. The steel reinforcement used was also tested using three specimens from each diameter.

Out of the 34 beams cast for the test series. The results for 27 beams are considered, as the rest were used to calibrate the testing equipment. Out of the 27 beams, 18 were tested dynamically and 9 statically. The conducted tests and the associated loading and reinforcement conditions are presented in Table 4.1, where the notation ”D” in the name stands for a dynamically tested beam and ”S” for the statical test. The notations ”S45, S90” stand for the distance between the vertical stirrups which is given in millimetres. The notation ”NoS” stands for no shear reinforcement. Finally, the notations ”0.4d, 1d, and 2d” indicate the distance from the support in terms of a ratio of the effective height, where the mass is dropped for the dynamic tests, and where the piston is applied during the static tests. A shear slenderness of 0.4, 1.0, and 2.0 was thus studied, assumed to result in direct shear failure, crushed compressive strut, and shear compression, respectively.
### Table 4.1: Declaration of beams and testing conditions.

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Beam name</th>
<th>Impact position</th>
<th>Vertical stirrups distance [mm]</th>
<th>Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>D-04d-S45-1</td>
<td>04d</td>
<td>45</td>
<td>1</td>
</tr>
<tr>
<td>B2</td>
<td>D-04d-S45-2</td>
<td>04d</td>
<td>45</td>
<td>2</td>
</tr>
<tr>
<td>B3</td>
<td>D-1d-S45-1</td>
<td>1d</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>B4</td>
<td>D-1d-S45-2</td>
<td>1d</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>B5</td>
<td>D-2d-S45-1</td>
<td>2d</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>B6</td>
<td>D-2d-S45-2</td>
<td>2d</td>
<td>45</td>
<td>4</td>
</tr>
<tr>
<td>B7</td>
<td>S-04d-S45</td>
<td>04d</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>B8</td>
<td>S-1d-S45</td>
<td>1d</td>
<td>45</td>
<td>5</td>
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<tr>
<td>B9</td>
<td>S-2d-S45</td>
<td>2d</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
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<td>04d</td>
<td>NoS</td>
<td>4</td>
</tr>
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<td>NoS</td>
<td>5</td>
</tr>
<tr>
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<td>D-1d-NoS-1</td>
<td>1d</td>
<td>NoS</td>
<td>6</td>
</tr>
<tr>
<td>B13</td>
<td>D-1d-NoS-2</td>
<td>1d</td>
<td>NoS</td>
<td>7</td>
</tr>
<tr>
<td>B14</td>
<td>D-2d-NoS-1</td>
<td>2d</td>
<td>NoS</td>
<td>7</td>
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<tr>
<td>B15</td>
<td>D-2d-NoS-2</td>
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<td>NoS</td>
<td>8</td>
</tr>
<tr>
<td>B16</td>
<td>S-04d-NoS</td>
<td>04d</td>
<td>NoS</td>
<td>9</td>
</tr>
<tr>
<td>B17</td>
<td>S-1d-NoS</td>
<td>1d</td>
<td>NoS</td>
<td>9</td>
</tr>
<tr>
<td>B18</td>
<td>S-2d-NoS</td>
<td>2d</td>
<td>NoS</td>
<td>9</td>
</tr>
<tr>
<td>B19</td>
<td>D-04d-S90-1</td>
<td>04d</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>B20</td>
<td>D-04d-S90-2</td>
<td>04d</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>B21</td>
<td>D-1d-S90-1</td>
<td>1d</td>
<td>90</td>
<td>11</td>
</tr>
<tr>
<td>B22</td>
<td>D-1d-S90-2</td>
<td>1d</td>
<td>90</td>
<td>11</td>
</tr>
<tr>
<td>B23</td>
<td>D-2d-S90-1</td>
<td>2d</td>
<td>90</td>
<td>12</td>
</tr>
<tr>
<td>B24</td>
<td>D-2d-S90-2</td>
<td>2d</td>
<td>90</td>
<td>12</td>
</tr>
<tr>
<td>B25</td>
<td>S-04d-S90</td>
<td>04d</td>
<td>90</td>
<td>13</td>
</tr>
<tr>
<td>B26</td>
<td>S-1d-S90</td>
<td>1d</td>
<td>90</td>
<td>13</td>
</tr>
<tr>
<td>B27</td>
<td>S-2d-S90</td>
<td>2d</td>
<td>90</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: Batches 15 and 16 were dedicated to manufacturing test beams.
4.2 Beam manufacturing

All the beams tested had identical geometry with a length of 800 mm and a cross-section of $150 \times 150$ mm. The flexural reinforcement consisted of three steel bars, each having a diameter of 8 mm, positioned 30 mm from the lower surface of the beam to the center of the bars. The compression reinforcement comprised two steel bars with a diameter of 6 mm and was located 30 mm from the upper surface of the beam to the center of the bars. The top side reinforcement was used to handle the failed beams after the experiment had finished and was only placed for practical reasons. Figure 4.1 shows the geometry of the cast beams and the different shear reinforcement configurations.

![Figure 4.1: Schematic representation of the beams with different shear reinforcement configurations.]

4.3 Material properties

Concrete strength

The compressive strength of the concrete used in this experiment was obtained by testing 16 cubes, in accordance with the recommendations of the SIS (SS-EN12390-3, 2019). Compression tests of 150 mm cubes were conducted giving the results presented in Figure 4.2. As seen, the concrete used in this experiment had a mean compressive strength of 43.7 MPa, which corresponds to a concrete strength class C35/45.
Steel reinforcement properties

The material properties of the steel used in the experiments were obtained through tension testing using three bars from each diameter, i.e. three bars with a diameter of 6 mm and three for ones with 8 mm. The results are presented in Figures 4.3 and 4.4.
4.4 Dynamic tests

The dynamic testing procedure involved dropping a cylindrical steel mass of 70 kg from a height of 2.4 m onto the beams. The beams were supported by half-cylinders of steel on both sides, which only restricted downward motion. To vary the impact position, the beam system was moved while maintaining the mass at the same position. The testing commenced after approximately 40-60 days of casting, see Appendix A, and a total of 18 beams were dynamically tested. Figure 4.5 illustrates the test setup.

The mass was guided during its free-fall by a plastic tube. The cylindrical mass was equipped with an accelerometer to measure the acceleration during impact. A rope was used to hoist the mass, which then was dropped from a height of 2.4 m over the surface of the beams. Figure 4.6 illustrates the cylindrical mass with the accelerometer and the rope used for hoisting.
Figure 4.5: The dynamic testing system with its main components.
Figure 4.6: The cylindrical mass used in the dynamic test, with an accelerometer on the upper surface.
In order to measure the reaction forces from the impact, two load cells were placed under the supports. The motion of the beam was measured by a shock accelerometer placed at the beam mid-point. Additionally, a steel half cylinder was placed on the beam’s surface at the drop point to distribute the impact more uniformly. The experimental setup is shown in Figure 4.7.

![Figure 4.7: The beam system with supports, load cells, and accelerometer.](image)

**4.5 Static tests**

The static testing of the beams was performed by an MTS machine which applied displacement at a rate of 0.5 mm/min. The maximum load from the piston was initially restricted to 130 kN to accommodate for the testing rig’s capacity but was later increased to 150 kN. A total of 9 beams were tested in static loading, with three beams for each reinforcement configuration and loading position. The tests were conducted about 60 days after casting.

The static testing setup is shown in Figure 4.8, where the concrete beams are supported by two roller supports at each side and the loading point varied in the same way as in the dynamic testing i.e. at distances 0, 4d, 1d, and 2d from one of the supports.
4.6 High-speed camera

The propagation of cracks in the dynamically loaded beams was investigated using a high-speed camera. The camera employed in this study was capable of recording up to 250,000 frames per second. However, the resolution was limited to $1024 \times 512$ pixels at a frame rate of 6,000 fps.

The high-speed camera was mounted at a distance of 2.1 m from the massive steel beam to eliminate any background vibrations that could interfere with the camera’s
precision. A LED lamp was also positioned in front of the beam to improve the clarity of the images. The arrangement is illustrated in Figure 4.9.
4.7 Eigenfrequency measurement

The eigenfrequency was measured during this experiment for the beams, both before and after the tests to investigate the reduced stiffness of the beams. The frequency was obtained by analyzing the signals from one accelerometer placed 50 mm adjacent to the mid-point. The input from an impact-hammer was also measured to determine the frequency response.

The beams were tested using a suspension system in order to eliminate any background noise that could affect the reading of the accelerometer as it was very sensitive. The suspension system utilized a massive and stiff steel beam laid on top of two chairs with two ropes lifting the tested beams. The stiffness of the steel beam together with the ropes eliminated the background noise. The setup is shown in Figure 4.10.

![Image of test setup for eigenfrequency measurement.

4.8 Filtering the results using MATLAB

In the present study, the MATLAB software (Inc., 2022) was utilized to filter the data obtained from all the instruments to reduce the noise that can be registered from the mass inside the accelerometer which results in peaky curves. To obtain the desired results, a filtering process was implemented on the measured data within the frequency range of 2000 to 2500 Hz. The filtering process resulted in a general deviation of less than 10%, see "Contact" in Figures 4.11 and 4.12. However, in some cases, the deviation was negligible. Figures 4.11 and 4.12 illustrate the measured forces, including three different curves. The "LC Close" force represents the reaction
force measured at the support closest to the load position. Similarly, the "LC Far" force indicates the reaction forces measured at the support located further away from the load position. Finally, the "Contact" force corresponds to the contact force recorded by the shock accelerometer.

Figure 4.11: The effect of data filtration in MATLAB for B11 where (a) represents the row data, and (b) represents filtered data.
4.8. FILTERING THE RESULTS USING MATLAB

(a) Without filtration.

(b) With filtration.

Figure 4.12: The effect of data filtration in MATLAB for B14 where (a) represents the row data, and (b) represents filtered data.
Chapter 5

Test results

This chapter presents test results from the experimental tests. The results are from a number of selected beams, all listed in Appendix A. Results were obtained by filtering the data obtained from load cells and the accelerometers installed on the mass and beams. Further, drawings and photos for some selected beams will be included. The drawings illustrate the crack pattern with a notation of crack widths, where only the cracks wider than 0.1 mm were considered.

The collected experimental data were subjected to analysis through the utilization of the numerical software MATLAB (Inc., 2022). The results were then presented in terms of forces, acceleration, velocity and displacement. Velocities and displacements were integrated from the acceleration signals over a time-span of 10 ms. Regarding the static tests, the data procured from the MTS testing machine was evaluated and expressed in the form of a Load-Displacement relationship.

5.1 Variation in load position

This section includes the results of the dynamically loaded beams with emphasis on the differences caused by different load positions for the same shear reinforcement configuration.

5.1.1 Beams without shear reinforcement

The results for the beams without any shear reinforcement are presented in Figures 5.1-5.3. In Figure 5.1, it is clear that the acceleration, velocity, and displacement increased as the load position moved from $0.4d$ to $2d$, as shown in Figure 5.1. It should be noted that there is a significant difference in both acceleration and displacement between beam B11 with load position $0.4d$ and the other two beams, which indicates a stiffer response from beam B11.
CHAPTER 5. TEST RESULTS

Figure 5.1: (a) Acceleration $a$; (b) velocity $v$ and (c) displacement $d$ for beams without shear reinforcement measured at midpoint.

Figure 5.2 shows a larger maximum contact force for load positions $0.4d$ and $1d$ from the support, compared to the load $2d$ from the support. The results also indicate that the maximum reaction force close to the impact decreases with increasing distance between support and load. Furthermore, the other support reaction shows an increase with increasing distance to the closest support. From the reaction force close to the load (LC Close), the concrete had a greater capacity regarding failure in shear by crushed compressive strut than the flexural shear capacity, see B11 and B14 in Figures 5.2a and 5.2c.
Figure 5.2: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer with varied load position and no shear reinforcement.
As shown in Figure 5.3, the beam subjected to loading at position \(0.4d\) (B11) failed due to a mechanism similar to a shear failure caused by a crushed compressive strut, as shown in Figure 3.3b, as the cracks extended from the support towards the impact point. The mechanism remained the same when the loading position shifted further away from the support to position \(1d\). However, when the loading position was increased to \(2d\), the failure mode was dominated by flexural shear failure, as the cracks propagated from the tensioned side of the beam and upward. It is also important to note that the number of measured cracks increased with the increase in distance between the loading position and the support.

![Figure 5.3: Cracks from dynamic loading of beams without shear reinforcement.](image)

### 5.1.2 Beams with S90 configuration

The results for the beams with S90 shear reinforcement configuration are presented in Figures 5.4 and 5.5. In Figure 5.4, it is clear, as for the beams without any shear reinforcement, that the acceleration, velocity, and displacement increase as the load position moves from \(0.4d\) to \(2d\). It is important to highlight the difference in acceleration and displacement between beam B24 loaded at position \(2d\) and the other beams. As B24 exhibited a much less stiff behaviour with higher acceleration and larger displacement.

Furthermore, it is clear from Figure 5.5 that the reaction force close to the impact load starts to decrease as the loading position moves from \(0.4d\) to \(2d\) while the reaction force far from the impact load starts to increase at the same time. The contact force is shown to be almost equal for the three loading positions.
As shown in Figure 5.6, the beams with loading positions $0.4d$ and $1d$ followed the exact failure mechanisms exhibited by the two beams, B11 and B13, loaded at the same positions presented in Figure 5.3, where B19 and B21 failed with the shear mode of the crushed compressive strut. In contrast, B24 failed in flexural dominated failure mode instead of the flexural shear failure mode of the beam B14 shown in Figure 5.3.

![Figure 5.4: Acceleration $a$, velocity $v$, and displacement $d$ for beams with shear reinforcement S90 measured at midpoint.](image-url)
Figure 5.5: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer with varied load position and shear reinforcement S90.
5.1. VARIATION IN LOAD POSITION

5.1.3 Beams with S45 configuration

The results for the beams with shear reinforcement S45 are presented in Figures 5.7 and 5.8. In Figure 5.7, it is clear, as mentioned before for the other configurations, that the acceleration, velocity, and displacement grow as the load position moves from $0.4d$ to $2d$, as shown in Figure 5.7. It is important to note the similarity in the behaviour of the beams with the S45 configuration and S90, as beam B6, similar to B24-S90, loaded at $2d$ showed less stiffness in its behaviour compared to the other beams.

Furthermore, it is evident from Figure 5.8 that the reaction force near the point of impact decreases as the loading position moves from $0.4d$ to $2d$, while simultaneously the reaction force farther from the impact load begins to increase. The contact force is shown to be almost constant for the loading positions $1d$ and $2d$, but it is smaller for the case of $0.4d$, which indicates a smaller shear capacity.

As shown in Figure 5.9, the beams with varied loading positions followed the same failure mechanisms exhibited by the beams presented in Figure 5.6, where B2 and B4 failed by the shear mode caused by a crushed compressive strut that can be seen from the diagonal crack pointing towards the load position. On the other hand, B6 obtained almost vertical cracks indicating a flexural failure mode.

Figure 5.6: Cracks from dynamic loading of beams with shear reinforcement S90.
Figure 5.7: Acceleration \( a \), velocity \( v \), and displacement \( d \) for beams with shear reinforcement S45 measured at midpoint.
5.1. **VARIATION IN LOAD POSITION**

Figure 5.8: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer with varied load position and shear reinforcement S45.
5.2 Variation of shear reinforcement

This section includes the results of the dynamically loaded beams, emphasising the differences caused by varied shear reinforcement configurations at fixed load positions.

5.2.1 Load at position 0.4d

The results for the beams with different shear reinforcement configurations are presented in Figures 5.10 and 5.11. As shown in Figure 5.10, the three beams obtain the same acceleration and velocity, except that the displacement decreases with increased shear reinforcement content.

Figure 5.11 shows that the maximum contact force is obtained for the beam without shear reinforcement and that the reaction forces are almost equal between the beams without shear reinforcement and the S90 configuration. In contrast, the reaction force of the beam with S45 reinforcement is significantly smaller than the other two.

As shown in Figure 5.12, it is clear that all three beams failed with a mechanism of shear failure by a crushed compressive strut. However, there is a slight difference as the beam without shear reinforcement (B11) obtained a slightly larger angle compared to the other two beams.
5.2. VARIATION OF SHEAR REINFORCEMENT

Figure 5.10: Acceleration $a$, velocity $v$, and displacement $d$ measured at midpoint for beams with different reinforcement configurations at load position $0.4d$. 
Figure 5.11: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer for beams with varied shear reinforcement configuration, loaded at the 0.4\(d\) position.
5.2. Load at position 1d

Results for the beams with different shear reinforcement configurations are presented in Figures 5.13 and 5.14. As shown in Figure 5.13, the beams with S45 and S90 configurations obtained almost the same acceleration, velocity, and displacement. However, the beam without any reinforcement gets a much larger acceleration, velocity, and displacement than the other beams. It is noteworthy to mention that the velocity of beam B13 decreased more slowly than the other two.

Figure 5.14 shows that the maximum contact force is obtained for the beam without any shear reinforcement, and it decreases with increased reinforcement content. Furthermore, the reaction forces are almost equal amongst the beams with shear reinforcement and slightly larger for the beam without shear reinforcement. The figure also shows a slight decrease in the contact force before reaching its maximal value for the beams with shear reinforcement, which is an indication of damage in the beam.

As shown in Figure 5.15, the failure mechanism for all three beams was shear failure caused by crushed compressive strut. It is clear that the number of observable cracks increased with increased shear reinforcement content, as the beam without shear reinforcement (B13) had the lowest number of cracks, and beams (B21) and (B4) with shear reinforcement configuration S90 and S45, respectively, had a similar number of cracks.
Figure 5.13: Acceleration $a$, velocity $v$, and displacement $d$ measured at midpoint for beams with different shear reinforcement configurations at load position 1d.
5.2. VARIATION OF SHEAR REINFORCEMENT

Figure 5.14: Reaction forces measured from the load cells, and contact force measured from the mass' accelerometer for beams with varied shear reinforcement configuration, loaded at the 1d position.
CHAPTER 5. TEST RESULTS

5.2.3 Load at position 2d

The results for the beams with different shear reinforcement configurations are presented in Figures 5.16 and 5.17. As shown in Figure 5.16, the beams with S45 and S90 configurations obtain almost the same acceleration, velocity and displacement. However, the beam without any reinforcement obtains a much smaller acceleration and displacement but practically the same initial velocity as the two other beams, except it decreases much more rapidly after the impact.

Figure 5.17 shows that the largest maximum contact force is obtained for the beam with shear reinforcement configuration S90 and a smaller minimum force is obtained for the beam without shear reinforcement. Furthermore, the reaction forces are almost equal amongst the beams with shear reinforcement and slightly smaller for the beam without shear reinforcement.

As shown in Figure 5.18, it is clear that the two beams with shear reinforcement failed with a flexural failure mechanism, with the cracks as the cracks in beam B24 with S90 configuration were more inclined. The beam B14 without shear reinforcement failed with a flexural shear failure mechanism which is indicated by the large inclination of the cracks.

Figure 5.15: Cracks from dynamic loading of beams, loaded at the 1d position.
Figure 5.16: Acceleration $a$, velocity $v$, and displacement $d$ measured at midpoint for beams with different shear reinforcement configurations at load position $2d$. 
Figure 5.17: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer for beams with varied shear reinforcement configuration, loaded at the 2\textit{d} position.
5.3 Variation of loading conditions

This section includes the results of the dynamically loaded beams in comparison to the statically loaded beams with equal shear reinforcement configuration at three different loading positions $0.4d$, $1d$, and $2d$. The emphasis is on the maximum load capacity demonstrated in the experiments and the deformation of the beams. The beams selected for this section have shear reinforcement configuration S90, as they were the only beams that produced acceptable results from the static tests.

In the results obtained from the static load tests, an initial displacement of 4 mm was observed, which could be attributed to the compression of the rig that contained the MTS machine before the deformation of the beams was initiated. The figures also display minor peaks, which can be traced to the loading process, as the load was stopped every 10 kN to study the progression of damage.

5.3.1 At loading position $0.4d$

Figure 5.19 presents the results of the statically loaded beam, indicating a maximum load of 130 kN and a maximum displacement of 10 mm. In contrast with B19, Figures 5.5a and 5.4 show the results of the dynamically loaded beam, highlighting a significant difference in loading capacity. Under dynamic conditions, the capacity, closely related to the contact force, was found to be around 295 kN, while the
displacement was almost identical to that of the statically loaded beam. A comparison between the two loading conditions is presented in section 6.3 to analyze the behaviour of the tested beams further.

5.3.2 At loading position 1d

The behaviour of beam B26 under static and dynamic loading was investigated using the MTS machine. The results show similarities with the previously discussed case, where the static load capacity was approximately 134 kN, as shown in Figure 5.19. Meanwhile, the dynamic load capacity of a similar beam, B21, was around 278 kN; see the contact force presented in Figure 5.14c. The displacement for the static loading case was approximately 10.5 mm, as seen in Figure 5.19. In contrast, for the dynamic loading case, it was approximately 12 mm, according to Figure 5.4.

5.3.3 At loading position 2d

The results obtained for beam B24 showed a similar trend as the previous cases, where the dynamic load capacity was more significant than the static. The static load capacity was found to be approximately 96 kN, according to Figure 5.19. In comparison, the contact force for a similar beam B24 when dynamically loaded was around 292 kN, as shown in Figure 5.5c. At this particular load position, the displacement during static loading was greater than during dynamic loading, with values of 18.4 mm and 13.9 mm, respectively, as depicted in Figures 5.19 and 5.4. It is important to highlight that beam B27 exhibited a significantly more ductile response in comparison to beams B25 and B26. This observation is evident from Figure 5.19, where the off-loading segment, after reaching ultimate strength, of the curve for B27 appears notably flatter and longer with increased displacement and constant load, compared to the shorter and steeper curves of beams B25 and B26. This behaviour suggests that the reinforcement in B27 experienced yielding.

![Figure 5.19: Force and displacement for statically loaded beams with shear reinforcement S90.](image-url)
Table 5.1: The dynamic load capacity for the beams B19-0.4\(d\), B21-1\(d\), and B24-2\(d\).

<table>
<thead>
<tr>
<th>Beam</th>
<th>Dynamic load capacity [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B19</td>
<td>295</td>
</tr>
<tr>
<td>B21</td>
<td>278</td>
</tr>
<tr>
<td>B24</td>
<td>292</td>
</tr>
</tbody>
</table>

As shown in Figure 5.20, it is clear that both the statically loaded beam (B25) and the dynamically loaded beam (B19) failed in shear by a crushed compressive strut. The beams with load at position 1\(d\) shown in Figure 5.21 obtained similar failure mechanisms, as for the beams loaded at 0.4\(d\), as both the dynamically and the statically loaded beam failed with a shear failure caused by a crushed compressive strut. The beams with load at position 2\(d\) shown in Figure 5.22 obtained similar failure mechanisms, as the two beams failed with a flexural shear mechanism.

Figure 5.20: Crack pattern for B25-D & B19-S at position 0.4\(d\).

Figure 5.21: Crack pattern for B26-S & B21-D at position 1\(d\).
CHAPTER 5. TEST RESULTS

5.4 Special cases

This section includes results from testing two interesting cases: removing the wooden fiberboard placed on the half cylinder where the mass was dropped and anchoring the flexural reinforcement to the beam.

5.4.1 Removal of fibreboard

To explore the influence of the fibreboard placed on the half cylinder, a test was conducted where the board was removed, as shown in Figure 5.23. The beam used for this test, B20, was designed with shear reinforcement, stirrups placed 90 mm apart. The results obtained from this test will be compared with those obtained from a similar beam, B19, which was tested with a fibreboard.

In the case of beam B20, the recorded reaction force (LC close) is approximately 253 kN, as presented in Figure 5.24b. In contrast, beam B19 exhibits a reaction force of around 238 kN, as shown in Figure 5.24a. These findings suggest that removing the fiberboard produces a more substantial reaction force and higher shear capacity. Additionally, removing the fiberboard resulted in an overload of the accelerometer attached to the mass. This indicates a significantly increased contact force; however, the precise magnitude of this increase could not be determined.

Figure 5.23: Beam B20 without a fiberboard.
5.4. SPECIAL CASES

(a) B19.

(b) B20.

Figure 5.24: Reaction forces measured from the load cells, and contact force measured from the mass’ accelerometer for B19 and B20. In B20 Contact forces is missing due to an overloading problem.

5.4.2 Anchorage of the flexural reinforcement

This section presents the findings from the investigation of the impact that anchorage of the flexural reinforcement could have on the beam. The anchoring process was executed utilizing welding to attach a steel plate on both sides of the beam, as illustrated in Figure 5.25. Further, the test was carried out on a beam (T5) without shear reinforcement and with loading at position 0.4d. The results were compared to those from a similar beam with identical reinforcement content and loading position. The results for both beams are illustrated in Figures 5.26-5.27.

Figure 5.25: Anchorage of flexural reinforcement.
According to Figure 5.26, beam T5 with anchorage showed a stiffer behavior compared to B11. This is seen from the beams’ acceleration and displacement, as T5 obtained slightly less acceleration and displacement. Furthermore, the stiff behaviour of beam T5 can also be seen from the beam rebound shown in the velocity curve.

![acceleration](image1.png)  ![velocity](image2.png)  ![displacement](image3.png)

Figure 5.26: Acceleration $a$, velocity $v$, and displacement $d$ measured at midpoint for beams T5 with anchorage and B11 without anchorage.

Based on the data presented in Figure 5.27, it is evident that anchoring of the flexural reinforcement has a significant impact on the reaction forces of the beam, particularly for the one furthest from the impact. This reaction force is observed to activate earlier for beam T5 and reaches a higher value than that recorded for beam B11. Additionally, the close reaction force is found to be slightly more significant for the case with anchorage than for that without anchorage.

Figure 5.28 shows that both beams failed with a similar mechanism: a shear failure caused by a crushed compressive strut. However, there are a few differences between the beams, as the beam with anchorage T5 obtained a significantly smaller shear crack than B11 but a higher number of minor flexural cracks. This again indicates the higher stiffness obtained from anchoring the flexural reinforcement.
5.5 Damage identifiers

This section includes the results from one factor used as a damage identifier in this experiment. The factor is the eigenfrequencies of the beams, which were measured both before and after testing, as mentioned in section 4.7.

The results of the measurements of the eigenfrequencies show an apparent reduction in the frequencies, indicating a reduction in the stiffness of the beams. This reduction is also seen in the form of a reduction in the mass of the beams. This is shown in Figures 5.29 and 5.30.
CHAPTER 5. TEST RESULTS

Figure 5.29: Difference in the eigenfrequency of the beams. *Damaged*: The support of the beam was damaged and the frequencies could not be determined.

![FREQUENCY MEASUREMENT [HZ]](image)

Figure 5.30: Difference in the mass of the beams.

![MASS MEASUREMENT [KG]](image)

5.6 Failure mechanism captured by high-speed camera

This section presents a series of high-speed camera images providing a detailed analysis of the failure mechanism observed in three different beams. The selected beams were chosen due to the interesting results they produced and did not contain any shear reinforcement. Moreover, they were loaded at three different positions. For each beam, three images are presented, with the first image captured before the crack propagation, the second image taken when the crack propagates, and the third captured after the beam failed.
5.6. FAILURE MECHANISM CAPTURED BY HIGH-SPEED CAMERA

5.6.1 Load at position $0.4d$

The series of images captured for this beam illustrate the progression of shear failure caused by a crushed compressive strut. The crack initiates from the support closest to the loading point, as depicted in Figure 5.31b, and gradually extends upwards at a slight angle towards the loading point, as shown in Figure 5.31c.

Figure 5.31: Crack propagation of B11 captured by high-speed camera during three different phases, (a) before the impact, (b) crack formation, (c) the final crack
5.6.2 Load at position $1d$

The beam loaded at position $1d$ exhibited cracks that started propagating from the nearest support to the loading position, as shown in Figure 5.32b, and moved upwards with a slight angle toward the load as shown in Figure 5.32c. Overall, the pictures captured of this beam show a similar failure mechanism to the beam loaded at position $0.4d$.

(a) At time $t = 0.0$ ms.

(b) At time $t = 1.5$ ms.

(c) At time $t = 25.3$ ms.

Figure 5.32: Crack propagation of B13 captured by high-speed camera during three different phases, (a) before the impact, (b) crack formation, (c) the final crack.
5.6. FAILURE MECHANISM CAPTURED BY HIGH-SPEED CAMERA

5.6.3 Load at position 2d

The captured images of this beam depict the progressive mechanism of flexural failure. The crack initiates from the tensioned side of the beam, as illustrated in Figure 5.33b, and moves upwards at a slight angle towards the loading point, as shown in Figure 5.33c.

(a) At time $t = 0.0$ ms.

(b) At time $t = 3.7$ ms.

(c) At time $t = 37.2$ ms.

Figure 5.33: Crack propagation of B14 captured by high-speed camera during three different phases, (a) before the impact, (b) crack formation, (c) the final crack.
Chapter 6

Discussion

6.1 Effect of load position

The beams were subjected to different load positions while keeping the same reinforcement configuration and content. It was found that the position of the load had an effect on the beams, most significantly when the load was located further away from the support, resulting in increased acceleration of the beams. This trend can be observed in Figures 5.1, 5.4, and 5.7. The reason behind this behaviour is that when the load strikes close to the support, mainly the shear mode of the beams is activated, neglecting the flexural mode. As a result, the beams experience difficulty in preventing crack propagation, causing the majority of the load’s energy to be dissipated through the cracks instead of being utilized to accelerate the beams. However, as the load moves away from the support, both shear and flexural modes come into play simultaneously. The combined effect of both modes hinders the propagation of cracks, which leads to an increase in the amount of energy from the load utilized to accelerate the beams. The difficulty in crack propagation can also be seen in the pictures captured by the high-speed camera, as the shear failure mechanism shown in Figures 5.31 and 5.32 took a significantly less amount of time to propagate compared to for the flexural dominated failure mechanism shown in Figure 5.33. The changes in failure mechanisms, as shown in Figures 5.3, 5.4, and 5.7, support this observation. The failure mechanism shifts from shear failure, characterized by crushed compressive struts and influenced by shear capacity, to flexural shear failure, governed by flexural shear capacity.

Additionally, it is worth mentioning that an unexpectedly large flexural shear crack was observed on the opposite side to the load of beam B14, which was loaded at a distance of 2d from the support. This failure is a flexural shear failure. A possible explanation for the loosened part from the unloaded side can be attributed to the splitting of the concrete cover, which arises due to the dowel action of the flexural reinforcement. This phenomenon occurs when the crack propagates as a flexural crack on the unloaded side. However, as the shear forces develop and deformation increases, primarily on the loaded side, the crack transitions into a shear mode and expands further on the unloaded side. Consequently, this expansion affects the flexural reinforcement, generating a dowel action that ultimately leads to the splitting of the concrete cover.
6.2 Effect of shear reinforcement

When comparing the results of the beams loaded at a distance of 0.4d from the support shown in Figures 5.10-5.12, it is evident that they exhibit similar behaviour and share the exact crack mechanism. However, a striking difference emerges in beam B19 with S90 shear reinforcement configuration, which displays lower acceleration, velocity, and deformation than the other beams. This outcome is unexpected, as it was anticipated that B19 would experience larger displacements than the beam with the S45 configuration. One possible explanation for this discrepancy lies in the failure mode of beam B19, where a significant portion of the support near the load undergoes crushing during loading. An alternative explanation could be the insufficient anchorage of the flexural reinforcement, which may result in a reduced ability of the beam to withstand deformations and maintain the integrity of its sides. Consequently, a substantial amount of kinetic energy from the mass is absorbed by the cracks. It is also noteworthy that beams with S45 and NoS configurations yield similar results, particularly in terms of shear capacity. Still, at the same time, this gave different displacements of the beams. This similarity could be attributed to the presence of stirrups, which create weaker cross-sections between them, possibly due to insufficient bonding between the steel and concrete. These weaker cross-sections fail early during loading, causing the dissipation of the mass’s kinetic energy through cracks instead of contributing to the beam acceleration and the development of the reaction force. In contrast, the NoS beam fails slightly later than both the S45 and S90 beams, allowing it to generate the reaction force.

Similar behaviour can also be observed for load positions 1d and 2d. However, it becomes apparent that the shear capacity differs among the beams, even though this discrepancy is not readily apparent in Figures 5.13 and 5.16. The variation lies in the crack patterns shown in Figures 5.15 and 5.18, where beams with S45 configuration exhibit cracks strongly influenced by bending moments. Similarly, beams with the S90 configuration display cracks primarily governed by bending but with a minor shear component. On the other hand, the NoS beams exhibit more inclined cracks with a more significant shear influence and less bending. This observation can be deduced from the crack Figures 5.12, 5.15 and 5.18, where the inclination of the cracks increases as the amount of reinforcement decreases. These findings indicate a difference in shear capacity among the beams.

6.3 Effect of dynamic loading

The data registered by the load cells indicate the beam’s dynamic load capacity. Compared with the static load capacity, it is clear that the beams had a greater dynamic capacity which is explained by the strain rate effect mentioned in section 2.2.5 and the inertia forces. This is due to the fact that when the cracks start to propagate under dynamic conditions, the stress does not have sufficient time to go through the path of least resistance, which is around the aggregate and goes through the aggregate instead, which requires an immense amount of energy which is translated into load capacity.
6.4 THE EFFECT OF THE FIBREBOARD

The crack pattern presented in Figure 5.22 shows that the beams loaded dynamically and statically had the same behaviour regarding the formation of the cracks. In an interesting case with load position $2d$, the number of cracks in the statically loaded beam was larger, and the width was more prominent than the dynamically loaded beam, which also can be attributed to the strain rate effect and inertia forces. Another significant impact of the varied loading conditions is evident in the residual eigenfrequency of the beams, as depicted in Figure 5.29. It is apparent that, overall, the statically loaded beams maintain a higher eigenfrequency compared to the dynamically loaded beams, suggesting a greater residual stiffness.

6.4 The effect of the fibreboard

The impact was softened using a fiberboard, and when the fiberboard was removed from beam B20 during the test, there was a noticeable difference in the results, as shown in Figure 5.24. The main distinction between the two cases was seen in the reaction force near the point where the load was applied. Without the fiberboard, the peak of the reaction force was sharper, indicating a more sudden release of the force, causing cracks to form in the beams. In the picture of beam B20 in Appendix B, it is evident that a considerable section of the beam experienced dislodgement subsequent to the impact. This can be attributed to the fact that the loading and unloading happened at a faster rate, which led to the crack propagating near the shear reinforcement. As a result, the loose part of the concrete was pushed out. Additionally, the weak bonding between the shear reinforcement and the concrete may have contributed to the formation of vulnerable sections that further amplified the problem.

6.5 The effect of anchorage

The impact of anchoring the flexural reinforcement is clearly visible in Figures 5.26-5.28, showing significant differences between the cases. The most noticeable distinction lies in the shape of the reaction force curves. In the beam with anchorage (T5), both reaction forces exhibit an earlier rebound and a much more substantial impact. This is attributed to the increased stiffness of the beams caused by anchoring the flexural reinforcement. As a result, the beam responds more forcefully to the applied mass. Moreover, anchoring the flexural reinforcement enables a faster transfer of the impact to the other support, further enhancing the beam response. The anchorage also restricts the beam from deforming significantly and, importantly, helps maintain the integrity of its side parts. In contrast, the beam without anchorage (B11) developed a crack in its side section.
Chapter 7

Conclusion and future research

7.1 Conclusions

This master thesis investigated the effects of load position, shear reinforcement, dynamic loading, fiberboard, and anchorage on the behaviour of reinforced concrete beams. The findings provide valuable insights into the structural response and failure mechanisms of such beams under varying conditions. The conclusions of this experimental study are as follows:

It was observed that the load position significantly impacted the beam acceleration. When the load was located further away from the support, both shear and flexural capacities came into play simultaneously. The failure mechanism shifted from shear failure to flexural shear failure as the load moved away from the support.

Beams with different shear reinforcement configurations exhibited similar behaviour, indicating the presence of weaker cross-sections caused by insufficient bonding between steel and concrete. A high amount of shear reinforcement resulted in slower acceleration of the beam. Furthermore, a difference was observed for the case when the beams were loaded at a distance of 2d from the support, as the shear reinforcement caused a flexural dominated failure mode instead of a flexural shear failure mode.

The study also examined the effects of dynamic loading on the beams. It was found that the dynamic load capacity of the beams exceeded their static load capacity, primarily due to the strain rate effect and inertia forces. The crack patterns and residual eigenfrequency of the beams differed under dynamic and static loading conditions, with dynamic loading resulting in more extensive cracking and reduced residual stiffness.

The use of a fiberboard provided a cushioning effect, as removing it during testing resulted in a more sudden release of force and the formation of cracks in the beams. Furthermore, the impact of anchoring the flexural reinforcement was evident in the shape of the reaction force curves. End anchorage significantly increased the stiffness of the beams, resulting in an earlier rebound and a more robust impact response.
7.2 Future research

The experiments conducted in this master thesis were designed to examine the behaviour of simply supported beams under dynamic and static loading conditions. It would be highly valuable to investigate the impact of altering the support boundary conditions, such as fixed support, which better represents the realistic support conditions of beams in practical applications where they are rarely simply supported and often fixed. This will enable more realistic analyses and a deeper understanding of reinforced concrete beams under natural conditions. Additionally, introducing variations in the beams’ dimensions would contribute to a more realistic experimental setup, as the dimensions used in this study were uniform and relatively small compared to typical dimensions of RC structures. Other intriguing factors to consider include adjusting the drop height, exploring different qualities of concrete and reinforcement steel, and varying the weight of the dropped mass.

Another noteworthy approach for analyzing the results would involve employing Digital Image Correlation (DIC). In conjunction with the high-speed camera, this technique allows for extensive strain field development and beam displacement analysis. A more comprehensive understanding of how the beams respond to various factors can be obtained by utilizing DIC, leading to more conclusive conclusions.

During the experiments, we encountered an issue with the loosening of certain parts of the beams and crack propagation between the stirrups. These issues could potentially be attributed to insufficient bonding between the steel and concrete or inadequate mixing of the concrete. To address this, it is crucial to ensure thorough cleansing of the stirrups and removal of any debris before pouring the concrete. Additionally, employing a highly efficient concrete mixer can help improve the bonding and mixing processes.
Bibliography


Ross, T. J., 1983. Direct shear failure in reinforced concrete beams under impulsive loading. Stanford University, California, USA.


## Appendix A

### Eigenfrequency and mass measurements

Table A.1: Eigenfrequency and mass measurements of the dynamically tested beams.

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Beam name</th>
<th>Before testing</th>
<th>After testing</th>
<th>Age [day]</th>
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<td></td>
<td>Mode 1</td>
<td>Mass [kg]</td>
<td>Mode 1</td>
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<td>49</td>
<td>X</td>
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<td>47</td>
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<td>506</td>
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Notes:

*: Selected beams.

X: Damaged support after the testing, invalid for measurement.
Table A.2: Eigenfrequency and mass measurements of the statically tested beams.

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Beam name</th>
<th>Before testing</th>
<th>After testing</th>
<th>Age [day]</th>
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Notes:

*: Selected beams.
X: Damaged support after the testing, invalid for measurement.
Appendix B

Drawings and photos of cracks
Figure B.1: B2 (D-0.4d-S45-2)
Figure B.2: B4 (D-1d-S45-2)
Figure B.3: B6 (D-2d-S45-2)
Figure B.4: B11 (D-0.4d-NoS-2)
Figure B.5: B13 (D-1d-NoS-2)
Figure B.6: B14 (D-2d-NoS-1)
Figure B.7: B19 (D-0.4d-S90-1)
Figure B.8: B21 (D-1d-S90-1)
Figure B.9: B24 (D-2d-S90-2)
Figure B.10: B25 (S-0.4d-S90)
Figure B.11: B26 (S-1d-S90)
Figure B.12: B27 (S-2d-S90)
APPENDIX B. DRAWINGS AND PHOTOS OF CRACKS

Figure B.13: T5 (D-0.4d-NoS)