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Behavior of structural members under oblique impact loads state-of-the-art review

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Abstract

During the life time of the structural members such as beams, columns and slabs, they are expected to be exposed to impact loads from falling objects, hit by cars, and ships with different weights, shapes and impact velocities. The previous studies were intensively studied the behavior of the structural members under lateral impact loadings. Yet very little attempts to understand the influence of the impact angle on the structural behavior of the members. Since failure of structural members can lead to the collapse of the entire structure, this study aims to understand how these members, behave and what causes them to fail under non-axial or lateral impact loads. Beams subjected to an inclined impact load are affected by several factors such as the speed and the mass of the impactor, the height of the dropped weight, the total impact energy, and the stiffness of the entire structure at the moment of impact. Previous studies shown that when the reinforced concrete slabs subjected to an oblique impact load the local damage occurs at a greater rate when the impactor hit the slab with angle of 20 degrees. However, the effects of the oblique impact load are still under research and more studies are required to understand that behavior.

Keywords: *Oblique impact, impact load, impact angle, impact velocity, critical load angle*

1. Introduction

Steel structures meet the requirements of efficiency, safety and adaptability, making them indispensable in the construction industry. More specifically, they provide affordable building solutions that are strong enough to withstand harsh weather and high forces, have low maintenance requirements, are efficiently manufactured, and are visually attractive to architects. Modern steel buildings have witnessed continuous improvement in recent years, ensuring their increasing importance in many high-rise and long-term projects. As a result, structural engineers have tried a number of approaches to see how to reduce the price of steel construction. The behavior of steel structural members under lateral loading has been studied extensively. Structural engineers are concerned with the behavior of steel structural members under dynamic impact loads, which may be the result of anything from mechanical failure to explosion to a terrorist attack to a car accident. The fall of Ronan Point in 1968 raised awareness among structural designers about the problem of slow collapse [1]. Researchers have understood the importance of studying these structural parts subjected to inclined impact loads. There are two main ways in which structural members may impact: axial and bending. The complex collapse that occurs in real car accidents is a combination of the two types of collapse, which is called an oblique impact that occurs at a certain angle. The average crushing loads for square-shaped, rectangular, and hat-shaped columns were also dealt with analytical investigations of axial impact loads have been described in detail [2-5]. When it came to deep bending failure of rectangular columns, Keckman [6] conducted the first thorough experimental examination. Using both stationary and movable hinge lines, he suggested several basic failure mechanisms. Wierzbicki et al [7] also came up with a comparable method, although they didn't test it. Wierzbicki [8] conducted studies regarding numerically simulated thin-walled columns. In actual collisions, however, columns usually collapse in a mixed mode that includes bending and axial collapse. Experiments conducted [9] on a hat-type column subject to an inclined impact load showed the necessity of studying this type of impact loads on the rest of the structural members.

Although studies in this field are rare, there are researchers such as Han and Park [10] studied thin-walled mild steel columns under the influence of impact loads. They created inclined surfaces by dropping the column against a sloping steel wall without creating friction.
Investigations conducted by Reyes et al [11] show that energy absorption decreases significantly when a loading angle of 5° is introduced to thin-walled aluminum during oblique loading. This is because the collapse mode changes as a result of the change in the direction of the impact and the strength of its impact. Abramowicz et al [12] is explained effect of thickness and heat treatment on the energy absorption capacity of aluminum alloys subjected to varying loads angles and temperatures were the primary objective of this study.
W.jang [13] was the first to study the axial impact loads of thin-walled square beams, and many other researchers have since investigated these beams' capacity to absorb energy through numerical and analytical studies. Researchers have also thoroughly examined bending impact loading using analytical and Finite Element (FE) methods. Additionally, by experimentation most of the research on shock absorbers on pure axial shocks and pure bending collapses was done [14–16]. Car accidents are realistic and can happen from any angle. This means that the impact loads to which cars are exposed may be loads at a certain angle, i.e. an inclined impact load. Pure bending or pure axial impact alone rarely occurs in car collisions, so attention has been drawn to a third type of impact, which is oblique; Instead, both types are frequently combined to cause collapses. If pure axial impact and pure curvilinear impact have received more attention, it is surprising that oblique or oblique effects have not.

2. Types of structural members that were studied when subjected to an oblique impact load

2.1. Thin-walled columns

Thin-walled members are exhibited excellent load-bearing capacity. Thin-walled columns are normally resisting axial load and moment and sometimes could be subjected to lateral or oblique impact loading during the lifetime of the structure. The cross-section of these columns is greatly affected when they are subjected to impacts. Therefore, they were the majority of research revolves around specific cross sections, such as square, circular, and hexagonal sections. Because of the ability of this type of columns to absorb energy, they are desirable in the manufacture that could be subjected to accidents. The impact energy is absorbed by these columns, causing the materials to deform. For many years, researchers have sought to understand the behavior of thin-walled columns under inclined impact loads to help designers meet their objectives for design competence. Analytical and experimental investigations into the prediction of collapse of thin-walled columns have focused on the structure's energy absorption properties [17]. Y.Liu [18, 19] studied the variables that affect the oblique impact load in the tests were the side lengths and wall thickness on square columns, straight and curved hexagonal columns, and octagonal columns .By adjusting the wall thickness and taper angle under oblique impact, as shown in Figure 1, it was found that the effect of the oblique impact load is a function of one variable, the loading angle, and that the wall thickness has a small effect on the failure load. A study was carried out on single and multi-cell square tubes to minimize PF (Peak Force) and optimize Specific Energy Absorption (SEA) by K.S.Bose et al [20]. After extensive computational and experimental simulations, the loading angle, material qualities, and geometric parameters like width, thickness, and length influence the collapse and cracking behavior of thin-walled square columns subjected to inclined loads. Table 1 shows the effects of different geometric properties when impact loads are applied to thin-walled columns in the inclined plane.

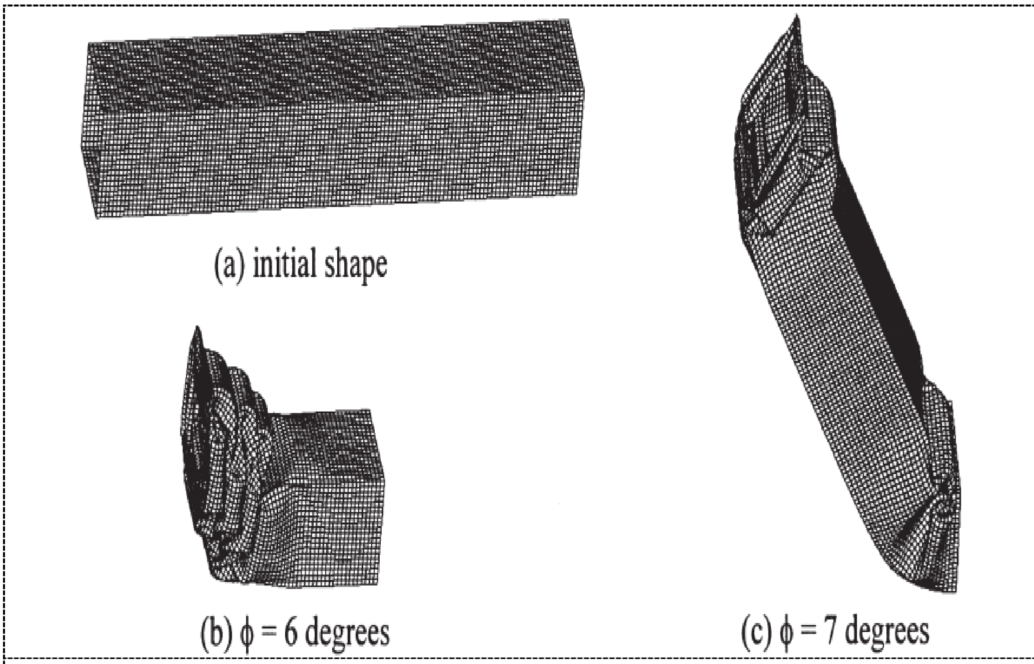

Fig. 1: The effect of an inclined impact load at different angles on a thin-walled column [20].

Table 1: Effects of different geometric properties impact loads applied to thin-walled columns in an inclined plane.

Study	Analysis	The main Parameters	Effectiveness
P.Hosseini -Tehrani [21]	Experimental and FE	Thickness of thin wall column	When a thin wall column is subjected to an inclined force, its average crushing load decreases as its thickness increases. The average crushing load is more sensitive to changes in thickness in the axial region compared to the bending region. Since a smaller effect of varying the thickness results in a lower load, the researchers deduced that the average crushing load is a function of just one variable—the load angle—and that increasing the load angle was the limit value that affected it.
Okubo[4]	Experimental and FE	Length And width	The results demonstrated that in the axial region, width is less sensitive to the average crushing force than in the bending zone. In fact, thickness has the opposite impact. In a similar vein, the average crushing load is width and length independent, with the exception of the bending zone.
M.Tani et al. [22]	Experimental and FE	Critical load angle	When the loading angle is zero, the average static crushing load is 1.45 times greater than the average crushing load under normal conditions. Although thickness has little to do with the critical angle range, length and width—specifically, the ratio of length to width—have a significant impact. However, the critical loading angle can be expressed in terms of length and width.

2.2. Thin-walled beams

The front shock absorbers of modern cars often use thin-walled beams. They are designed to distribute impact energy evenly along the collapse, minimizing injury to vehicle occupants in the event of an unexpected accident, and they also save significant amounts of energy dissipation. The majority of research conducted on shock absorbers has focused on bending or axial impact load alone. Car accidents can occur from any direction. It is unusual for a car accident to occur along straight lines or in axial bends alone. Both types of impacts can occur in car accidents. Researchers have paid more attention to straight axial and bending impacts than to oblique impacts. Analytical studies were conducted on steel beams subjected to biaxial inclined loads for civil engineering purposes, and as shown in Figures 2, 3, the failure modes of thin-walled beams under the influence of oblique impact load. Further research into this area is required, as demonstrated by H.F.Mahmood et al [23] experiments and studies conducted on a hat section column subjected to inclined impact loads. Additional numerical investigations concerning slanted loading: A method for simulating the slanted loading test was employed, which involved the axial impact of beams on a solid wall that was angled at different degrees [10]. The experimental and numerical behavior of square aluminum beams subjected to inclined loading was investigated by Wallentowitz et al [9]. Additional research by N.E.Shanmugam et al [24] used quasi-static loading to examine the effects of inclinational impact loads on square and round aluminum tubes filled with foam .Although tapered beams are an efficient means of increasing resistance, Reyes et al [25] found that they absorbed less energy per unit weight in axial impacts compared to conventional beams, and they also focused on enhancing the performance of tapered beams under inclined loads table 2 shows effects of different geometric properties impact loads applied to thin-walled box beams in an inclined plane.

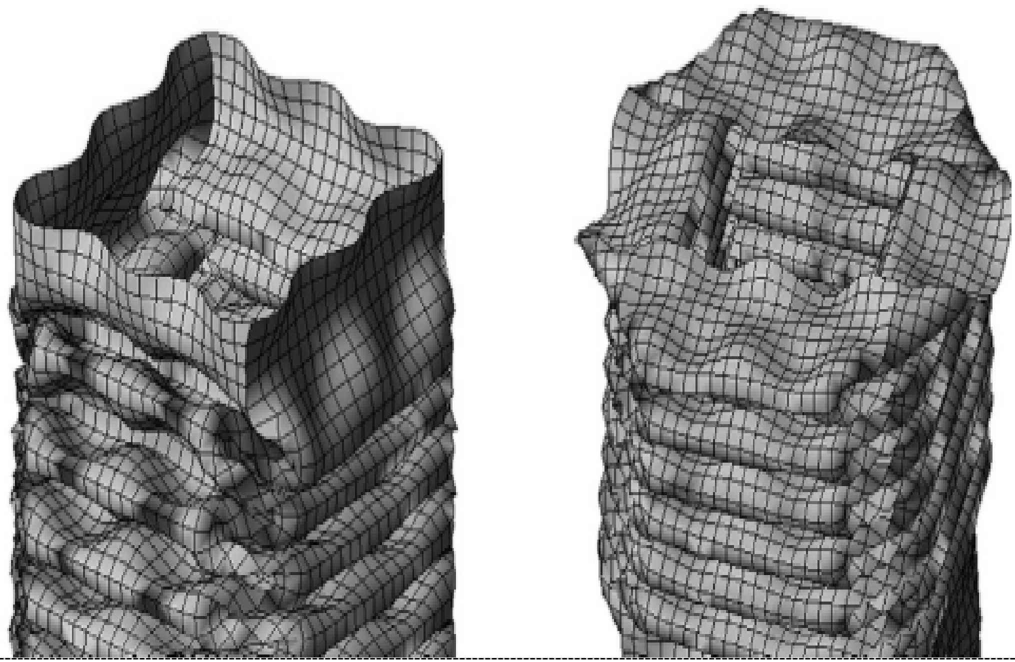

Fig. 2: Collapse modes of thin-walled beams [26].

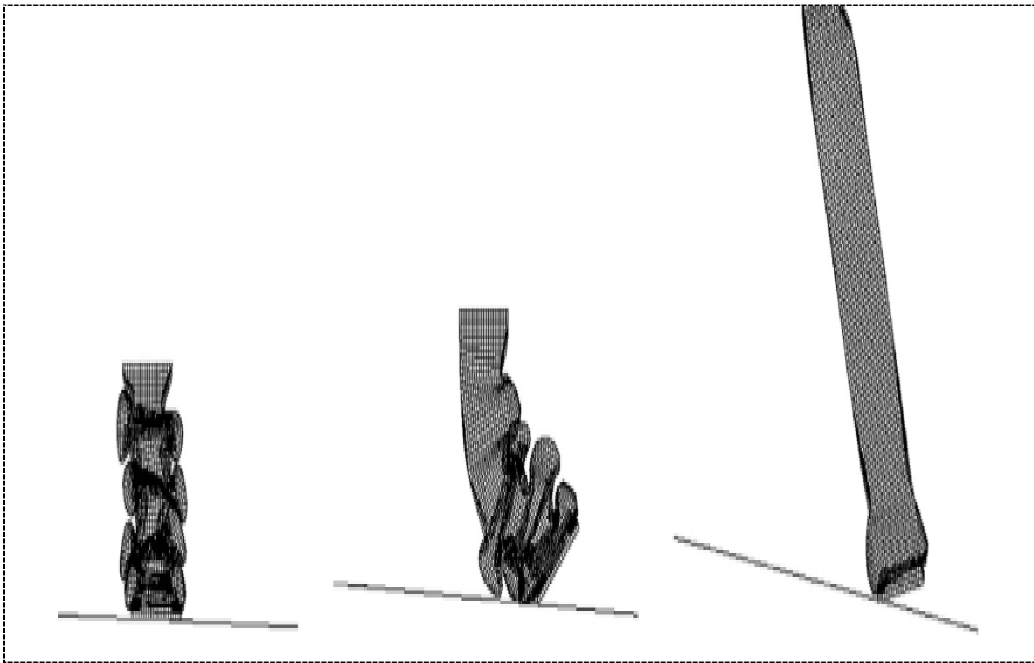

Fig. 3: Behaviour thin-walled beam under oblique impact load [27].

Table 2: Effects of different geometric properties impact loads applied to thin-walled beams in an inclined plane.

Study	Analysis	Parameter	Effectiveness
Liu [28]	FE	Impact velocity	The peak crushing force is affected by the initial impact velocity, but the average crushing force is not significantly changed. The impact velocity has no effect on the collapse mode.
Jones [29]	FE	Critical impact angle	With a critical angle of about 21°, the reference model's average collapse strength behaved worse than an angle of 41°.

2.3. Reinforced concrete slabs

Researchers used analytical methods to study perforation damage in reinforced concrete slabs that were struck indirectly by solid projectiles in several investigations. A number of factors determined the extent of local damage to reinforced concrete slabs including, thickness, impact speed, and impact angle. Kennedy [30] investigated various experimental methods to study local damage. Structural damage resulting from the collision of an aircraft engine with a reinforced concrete structure was studied by Sugano et al [31] in a series of crash tests that included small, medium, and large-scale impact experiments using rigid and elastic projectiles, in that order. The tests were reviewed by Sugano et al., who demonstrated a suitable experimental method to estimate the local damage that solid missiles can cause as shown in Figure 4 an experimental apparatus for applying an impact load at an angle to a concrete slab. Later, Li et al [32] presented the latest developments in calculating and simulating the local damage to the RC structure caused by strong impact, it was also found that the deformation resulting from a flat impactor is larger than that resulting from a hemispherical impactor as shown in Figure 5, which indicates that the effects of different impactor shapes on the RC slab are different [33]. Table 3 shows effects of different geometric properties Impact loads applied to reinforced concrete slabs in an inclined plane.

Fig. 4: The experiment's setup [31].

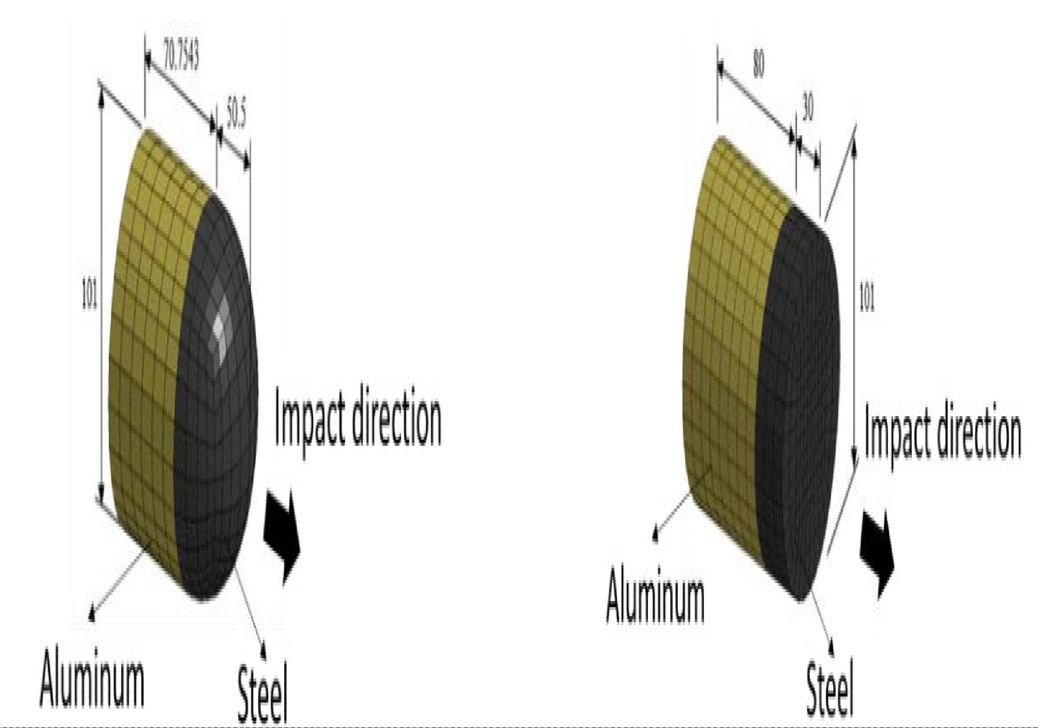

Fig. 5: Types of impactor shape [34].

Table 3: Effects of different geometric properties impact loads applied to reinforced concrete slabs in an inclined plane.

Study	Analysis	Parameter	Effectiveness
Sugano et al.[31]	Experimental and Theoretical	Shape of the impactor head	1. The comparison results showed that when the concrete slab is subjected to an inclined impact load with an impact angle of 45 degrees, the residual velocity of the hemispherical impactor is almost 2.6 times higher than that of the flat impactor. The value is 1.1 to 1.4 times more than the flat-shaped impactor's remaining velocity at impact angles of 0, 15°, and 30°. 2. Throughout the experiment, it was noted that the concrete slabs back face had a generally bigger damage area than its front face, and that the density of cracks on the back face was significantly higher than on the front faces. This phenomenon is attributed to the strengthening of the steel that occurs in cases of flat-shaped projectiles. More dangerous than what occurs in hemispherical-shaped projectiles. 3. When subjected to a flat-shaped impactor, the concrete slab sustains more localized damage than when exposed to a hemispherical-shaped impactor.

2.4. Composite sandwich plates

Advanced structural composites with high stiffness-to-weight ratios, or composite sandwich structures, have become more and more popular in recent years for a variety of lightweight structural applications. High-performance aircraft components typically use sandwich constructions, which are composed of a honeycomb core and thin composite facing sheets. When it comes to low-velocity impact events that can happen during manufacturing, transportation, installation, and maintenance procedures, thin composite face-sheets are particularly vulnerable to damage. In this case, low impact energy levels may result in little to no impact damage or very little damage at all, but they may also significantly reduce the composite sandwich structure's residual strength (up to 50%) and local stiffness.

Numerous academics have examined how composite sandwich structures behave under normal impacts such as (lateral, axial impact) [35-42]. The low-speed incline impact behavior of sandwich constructions made of composite materials has not been thoroughly studied. In addition to using numerical analysis to determine the impact of the puncture energy with the tilt angle, I. Ivañez et al [43] studied the influence of the tilt angle on the puncture resistance of three panels, similar responses were seen in all three panels, suggesting that the hole energy rises with impact angle. The majority of impact impacts occur at an angle. The majority of oblique impact experiments were conducted in high-speed impact environments [44, 45]. Experimental studies have shown that the impact angle and impact energy, as well as the degree to which they influence the maximum contact force, maximum contact time, absorbed energy, maximum impactor displacement, and the damaged area, are the geometric parameters that determine the inclined impact load of composite sandwich panels as shown in Figures 6 and 7. When the impact energy and angle increase, the energy absorption and maximum load, but contact duration essentially stays constant. If the angle of the oblique impact load is less than 15 degrees, the panels are unaffected. As the angles of impact increase, the maximum contact force decreases. Table 4 shows the effect of different parameters on impact behavior of the composite sandwich plates that positioned in an inclined plane.

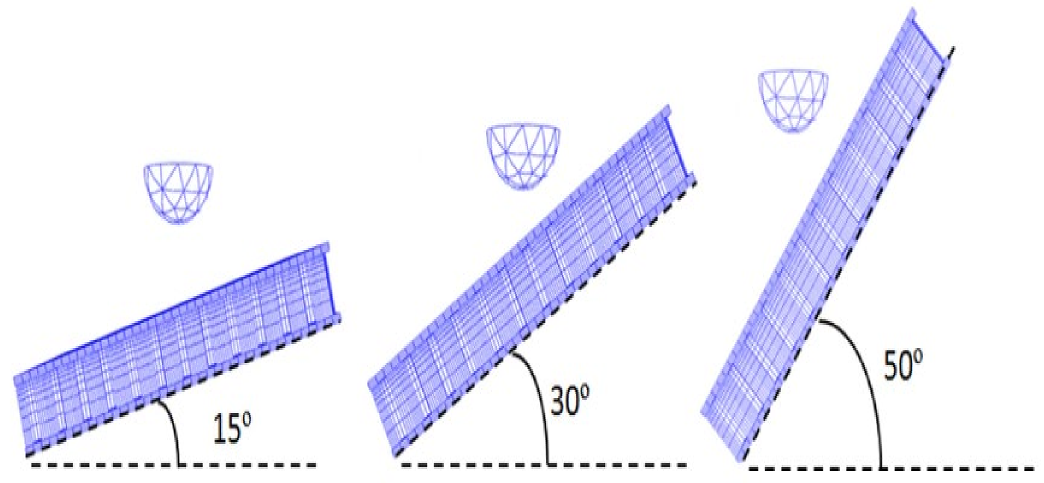

Fig. 6: Several impact angles were examined [46].

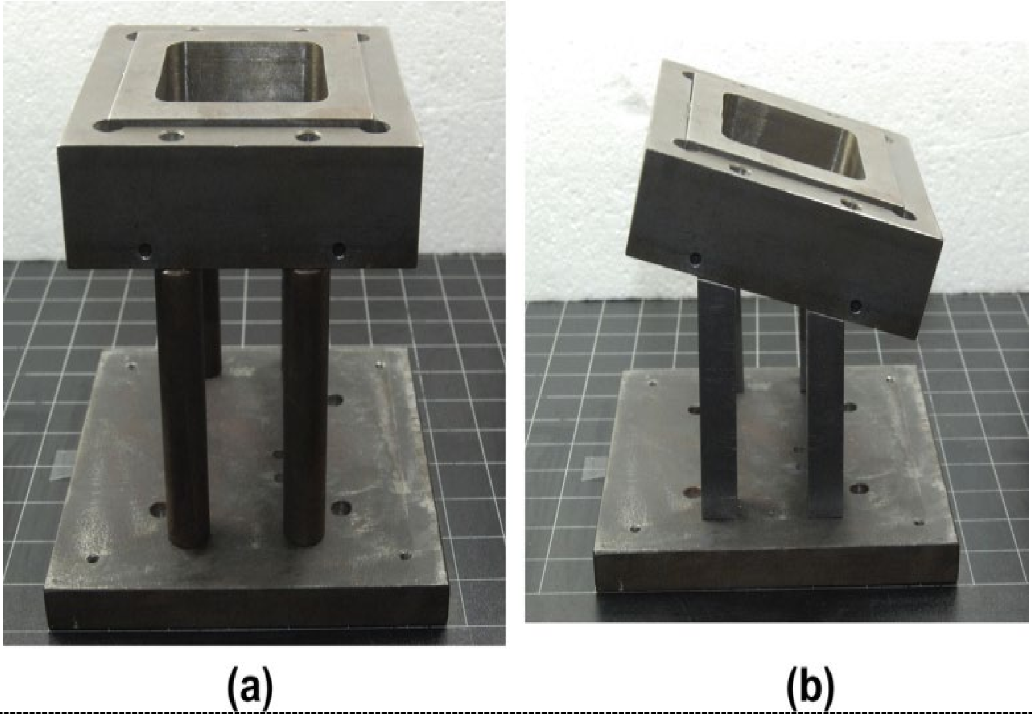

Fig. 7: The oblique impact tests are conducted using the following inclination angle devices: (a) 0 and (b) 15° [47].

Table 4: Effects of different geometric properties impact loads applied to composite sandwich plates in an inclined plane.

Study	Analysis	Parameter	Effectiveness
S.Sánchez Sáez [48]	Experimental and FE	Angle of impact and maximum displacement	At an angle of 0 and 5° the composite sandwich panels absorb more impact energy the larger the impact angle. Although an impact angle of 10° increases the power. In other words, as the impact angle increases, the energy absorbed also increases. variation between the impact energy and the maximum displacement of the impact. As the impact energy rises, the maximum displacement rises rapidly. In other words, since the angle of impact is regarded as a separate independent parameter, the maximum displacement rises as the angle of impact does.
S.K.García-Castillo [49]	Experimental and FE	Greatest force of contact	The maximum contact force as a function of impact energy is affected by the impact angle. While the contact force increases approximately linearly with increasing impact energy, the maximum contact force decreases with increasing impact angles.

2.5. Square aluminum tubes

Aluminum alloys are becoming more and more common in constructions where environmental considerations demand low weight. When compared to conventional steel buildings, the weight can be reduced by up to 25%. The automotive sector finds aluminum to be a material that is appealing, low weight lowers emissions of carbon dioxide and fuel usage. Aluminum provides additional environmental benefits due to its recyclable nature. Many years of intensive research on thin-walled columns have produced formulas for mean forces and bending moments [16, 50]. During a real failure event, the energy absorber is rarely subjected to pure axial loading or pure bending; instead, a combination of both loading conditions occurs. The bumper system must be able to support an applied load with an angled effect and a loading angle of 30 to the longitudinal axis in accordance with industry standards for bumper systems. The behavior of square aluminum columns with thin walls under inclined loading was examined, and the Eurocode9 was put to the test experimentally at various aluminum alloy temperatures and load angles [51]. While there aren't many studies in this area, some have been done numerically. Han and Park [52] examined mild steel columns with thin walls that were loaded at an angle, they achieved an inclined situation by striking the column with a frictionless steel wall. The crushing behavior of thin-walled columns under coupled bending and compression was investigated by Kim and Wierzbicki [7]. They discovered that the analytic model could predict the numerical data and that the failure sites reduce as deformation increases, as shown in Figure 8. Examining the energy absorption capability of thin walls and the impact of thickness and heat treatment was the primary goal of this work. Table 5 shows effects of different geometric properties impact loads applied to square aluminum tubes in an inclined plane.

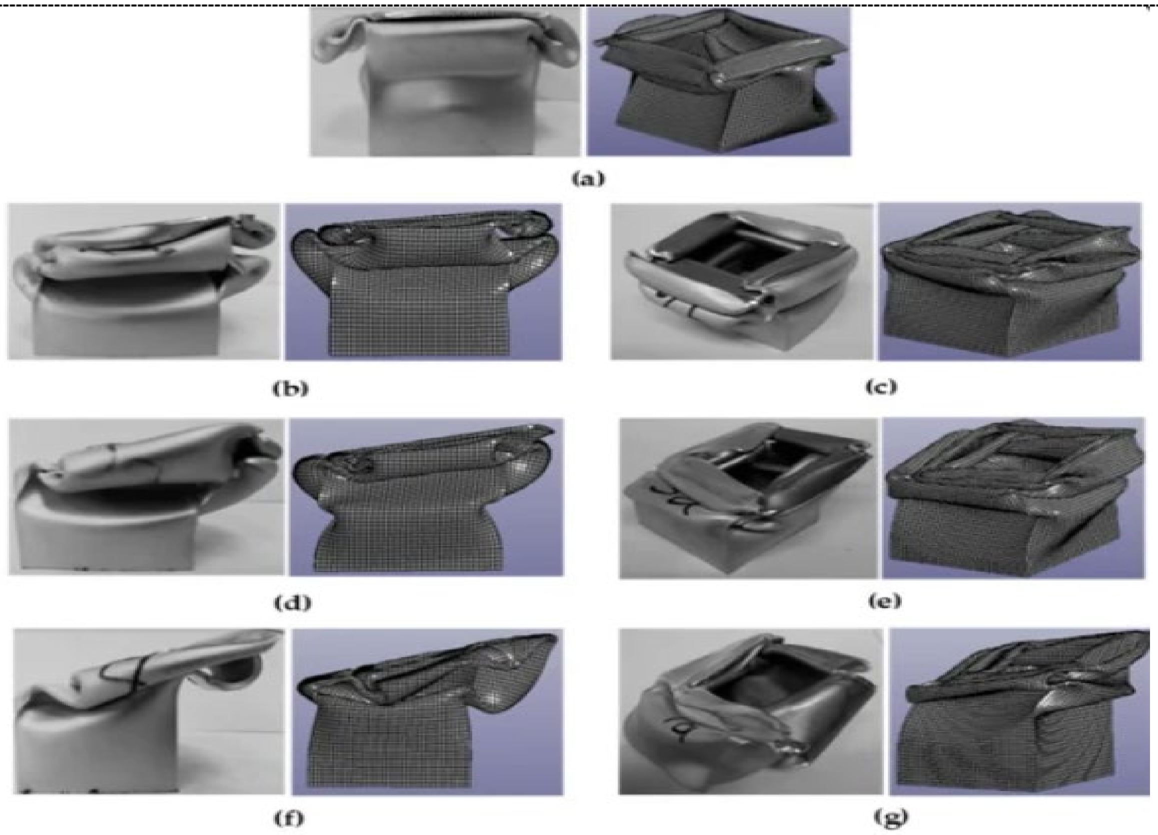

Fig. 8: Failure modes of square aluminum tubes under different angle and location of oblique impact load [53].

Table 5: Effects of different geometric properties impact loads applied to square aluminum tubes in an inclined plane.

Study	Analysis	Parameter	Effectiveness
T. Børvik et al. [54]	Experimental and FE	Impact angle and thickness	At greater angles, peak loads likewise decrease, but the force level does not. Greater strength is seen in thicker tubes.
M. Langseth et al. [55]	Experimental and FE	Energy absorption	As the loading angle increases, energy absorption further decreases.

3. Conclusion

This study sheds light on the behavior of certain types of structural elements under oblique impact load, understanding the failure mode and the influence of various factors such as critical loading angle, loading speed, impact head shape and other factors. Influence on the behavior of structural members under diagonal impact load including thin-walled columns, thin-walled beams, reinforced concrete slabs, aluminum square tubes and Composite sandwich plates. The purpose of this review is to explore the structural behavior of these members under oblique impact loads. Furthermore, the following conclusions can be drawn from the reviewed papers:

1. With regard to thin-walled columns when subjected to an inclined impact load, the geometric parameters affecting them are thickness, length and width of column. It has been observed that when the column is exposed to an inclined impact force, the crushing load decreases with the increase in column thickness. Also, length and width are factors affecting the column only in Bending area.
2. Thin-walled box beams, when subjected to an inclined impact load, are affected by several geometric parameters, including the impact velocity as well as the critical impact angle, as it was observed that at an impact angle of 21°, the impact load has a stronger effect on the beam than at an impact angle of 41°.
3. One of the engineering parameters affecting reinforced concrete slabs when subjected to an inclined impact load is the shape of the impactor head. It was found that when the slab is exposed to a flat-shaped impactor, the local damage is greater than an impactor with a hemispherical shape.
4. Regarding sandwich panels installed under the influence of an inclined impact load, they are affected by the impact angle. It was noted that the greater the angle of impact, the greater the absorbed energy as well. This means that at an impact angle of 10, the absorbed impact energy is greater than at an impact angle of 0 and 5°.
5. For square aluminum tubes, when subjected to an inclined impact load, they are affected by three important geometric parameters: impact angle, thickness, and energy absorption. When the loading angle is large, the maximum loads decrease, but the strength level does not decrease. Also, when the pipes are thick, they show greater strength, and by increasing the loading angle, energy absorption decreases more.
6. As for solid and hollow steel columns, there has been no study to understand their behavior under the influence of inclined impact loads and what are the influential geometric parameters.

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