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CRASH SAFETY OF A TYPICAL BAY TABLE IN A RAILWAY VEHICLE

Summary. Increasingly, urban and high speed trains are incorporating tables (workstations) as common railway vehicle interior furniture because passengers prefer seating by bay tables. Among table design characteristics, the most challenging is meeting crashworthiness requirements. Past accident data and sled test results have shown that in the event of railway vehicle frontal impact, occupants located in the bay seating are exposed to chest and abdominal injuries upon contact with tables resulting from secondary collision. In some cases tables have tended to be structurally weak; they easily detach from the side walls and/or floor mounting. Subsequently these become unguided missiles that strike occupants, resulting in injuries.

This paper presents an analysis of the crash performance of a typical bay table. The results provide some understanding of the table's crash safety, giving an indication of its impact aggression. Table materials are characterised using quasi-static compressive tests. In addition, experimental dynamic (impact) tests are conducted using a pendulum representing a body block (mass). The results provide information about the possible loading of the table on the occupant in the event of a crash. Contact forces are compared with chest and abdominal injury tolerance thresholds to infer the collision injury potential. Recommendations are then made on design of bay tables to meet the "functional-strength-and-safety balance".

TESTY BEZPIECZEŃSTWA TYPOWYCH STOŁÓW WYKORZYSTYWANYCH W POCIĄGACH

Streszczenie. Coraz częściej zarówno w pociągach miejskich, jak i pociągach dużych prędkości wprowadza się do wyposażenia stoły. Wynika to z wymagań pasażerów, którzy to preferują siedzenie przy stołach. Wśród cech konstrukcyjnych stołów, największym wyzwaniem jest spełnienie wymagań wytrzymałości zderzeniowej. Wcześniejsze informacje dotyczące wypadków i wyniki badań wykazały, że w przypadku czołowego zderzenia pojazdów kolejowych pasażerowie, znajdujący się w sąsiedztwie stołów, są narażeni na urazy klatki piersiowej i brzucha na skutek wtórnej kolizji. W niektórych przypadkach stoły miały słabą strukturę; w prosty sposób można je było odłączyć od ścian bocznych i/lub podłogi, do których były przymocowane. W następstwie stawały się one niekontrolowanymi pociskami, które uderzały pasażerów i powodowały ich obrażenia. W artykule przedstawiono analizę wyników wypadku dla typowego stołu. Wyniki dostarczają wiedzę o bezpieczeństwie w razie zaistnienia wypadku z udziałem stołu, podają informacje o skutkach. Materiały stosowane na stoły zostały zbadane za pomocą quasi-statycznych testów ściskających. Ponadto, przeprowadzono eksperymentalne dynamiczne testy wykorzystujące wahadło. Wyniki dostarczają informacji na temat potencjalnego oddziaływania stołu na pasażera w momencie zderzenia. Siły kontaktowe są porównywalne z progami tolerancji, odpowiadającym klatce piersiowej i jamie brzusznej, w wyniku czego można przewidzieć skutki kolizji. W związku z tym zaleca się wykonanie stołów z zachowaniem „równowagi funkcjonalności, wytrzymałości i bezpieczeństwa”.

1. INTRODUCTION

While significant achievement has been made in reducing the maximum crash pulse to 5g as per EN 15227 standard [1], much still needs to be done to reduce injuries caused by secondary collision of occupants with the train interior furniture. Such secondary collision objects include seats, tables, partitions, side walls and floor. A report by RSSB [2], indicates that most of the ‘unknown causes of injuries’ stem from secondary collisions. One such object is a table, particularly bay tables.

Increasingly, urban and high speed trains are incorporating tables (workstations) as common railway vehicle interior furniture due to the fact that passengers prefer seating by bay tables. Such tables require certain design characteristics notably the aesthetic, weight, space provision for passenger comfort, structural integrity as well as crashworthiness capability for occupant protection in a crash

1.1. Design of Tables in Railway Vehicles

Among all these design characteristics, the most challenging is meeting crashworthiness requirements. This is because some accident data and sled test results have shown that in the event of railway vehicle frontal impact, occupants located in the bay seating are exposed to chest and abdominal injuries upon contact with tables. Some accidents data have also shown that bay tables are designed too stiff and of certain shape that easily injure occupants upon collision. On the other end of the spectrum, some tables have tended to be structurally weak so they easily detach from the side walls and/or floor mounting. In such cases, these tables become unguided missiles that strike occupants, resulting in injuries.

1.2. Typical Recent Past Accidents Involving Fixed Tables

A number of train accidents have occurred in the last 5 years. Two of them stand out as being relevant to secondary collision injuries causes by train tables. On 17 August 2010, a train collided with a sewer tanker in Suffolk, UK [3]. More recently, on 21 April, 2012, there was a head on train collision in Amsterdam [4].

1.2.1. Amsterdam (Netherlands) April 2012

On 21 April 2012, a head-on train collision occurred in Amsterdam, near Westerpark [4]. It involved a sprinter and an intercity train. At least 190 out of 425 occupants were injured, out of which 24 sustained serious injuries, one of which was fatal. The accident report prepared by the Dutch Safety Board (DSB) indicated that although the collision was forceful, the trains did not derail, and no occupants were trapped. Injuries sustained were mainly caused by secondary collision of the train interior (such as seats, tables, glass partition walls and partition doors) and with other passengers.

Two occupants of the first coach were injured due to being hit in the abdomen by a fixed table, while occupants of other coaches were hit in the chest.

To minimise injuries caused by tables, installation of tables that are collision-friendly was recommended. Further, to minimise the distance through which occupants are projected, some kind of special (interceptor) tables could be installed.

1.2.2. Suffolk (UK) August 2010

The design characteristics of the tables in terms of being too strong or too weak can be summed up in two BBC reports. Soon after the accident, a BBC report quoted one of the injured as saying “I felt a sudden collision as the train didn't slow down. I shot forward and hit the table and I banged my chest” [5]. This may indicate that the table was too strong and impact aggressive. On the other hand, a later BBC report indicated that “The RAIB report includes pictures which show how the legs of the tables bent, thrusting the tables towards passengers”. This shows that some tables broke loose, implying that the tables may have been too weak.

Details of the accident investigation by the Rail Accident Investigation Branch (RAIB) relevant to table safety are summarised below [3]:

The collision caused the train to derail. Several passengers and the conductor on the train were injured in the collision. The rear coach remained on the rails but suffered minor external damage. Both coaches had internal damage to doors, tables and fixings with some of the damage arising from passenger impact.

Although the train involved in the accident was not designed to withstand a collision with a large goods vehicle, the majority of the injuries were caused by the interaction of passengers and tables rather than by structural deformation of the vehicles themselves. The design of the tables may have contributed to the severity of the consequences of this accident.

Tables were either deformed (Fig. 1) or detached (Fig. 2).

Due to the injuries caused by tables, one of the recommendations made in the report was: “a review of the crashworthiness performance of the tables in the type of train involved in the accident”.

Fig. 1. Typical example of table deformation
Rys. 1. Typowy przykład odkształcenia stołu

Fig. 2. Typical example of table detachment
Rys. 2. Typowy przykład oderwania stołu

1.3. The Research Challenge

Although standards such as the GM/RT2100 Issue 5 [6], stipulate the minimum (horizontal loading) strength of a bay table, they do not provide a means to provide corresponding measurable link to the injury potential on the occupant.

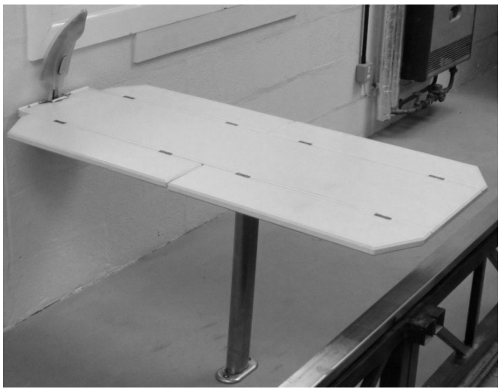
The challenge is: how strong is too strong so that the tables do not cause serious injuries; how weak is too weak so that the tables do not detach and encroach into the survival space of other passengers?

This paper presents strength characterisation of a typical European bay table from a TGV Eurostar high speed train. It shows table performance results from quasi static and impact tests. The results also helped in the understanding of possible loading of the table on the occupant in the event of a crash. A methodological approach was developed to infer the loading on the thorax. It assumes that tables are much more rigid than human body tissue.

2. METHODOLOGY

2.1. Material Characterisation

Experimental material characterisation of the bay seating TGV Eurostar train foldable table provided by Siemens of Germany was carried out. Two types where considered – the larger First Class and smaller Standard Class tables (see Fig. 3).



(a) First Class Bay Table

(b) Standard Class Bay Table

Fig. 3. High Speed Train TGV Table
Rys. 3. Stół w pociągu szybkich prędkości TGV

Both types of tables used a similar stainless steel pedestal. However, the side fixings were different. The former was made of mild steel, while the latter was made of cast aluminium.

A 250 kN capacity Instron Universal Testing Machine was used to conduct quasi-static tests. This was done only for pieces of specimens constituting the edge of the table relevant to the expected loading from an occupant colliding with a table. The specimens were loaded under compressive load. This is because during a frontal collision between an occupant and a bay table, the thorax (chest or abdomen) gets in contact with the edge of the table, creating a compressive contact load. See the illustration in Fig. 4.

To characterise the material behaviour of the whole table, a pendulum impactor was used to provide dynamic loading.

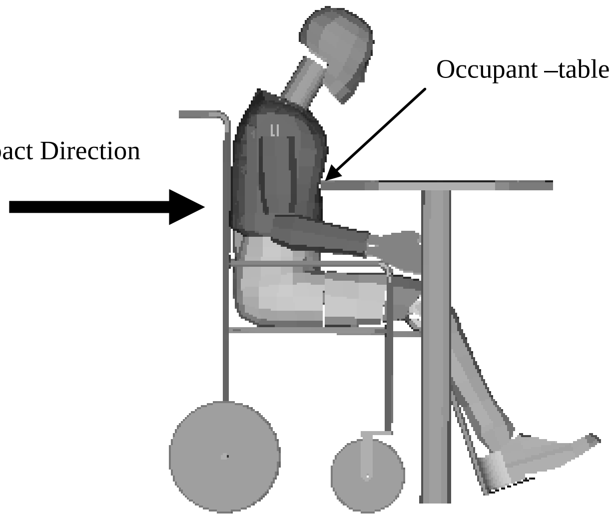


Fig. 4. Wheelchair occupant collision with a bay table
Rys. 4. Osoba na wózku inwalidzkim podczas kolizji ze stołem

2.1.1. Quasi-static tests of Components of the Bay Table

Compression tests were used to determine the mechanical properties of the edge of the table. Fig. 5 shows the table transverse cut out that reveals the interior. Particular emphasis was made to the part that interacts or has potential to interact with occupants during a crash.

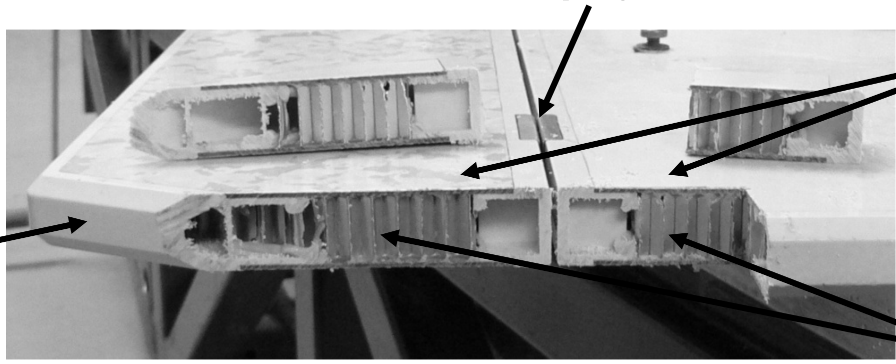


Fig. 5. Interior Structure of High Speed Train TGV Table
Rys. 5. Struktura wewnętrzna stołu z pociągu TGV

The table top (which is the main impact component) was made of a composite comprising an aluminium honeycomb core sandwiched between Formica laminates, while the edges were made of thermoplastic. It was observed that First Class and Second Class tables were the same in terms of the materials used to construct them. The shape was similar, but differed in geometrical dimensions of the table top. The former was larger.

Fig. 6 shows a typical example of the test setup for compressive load.

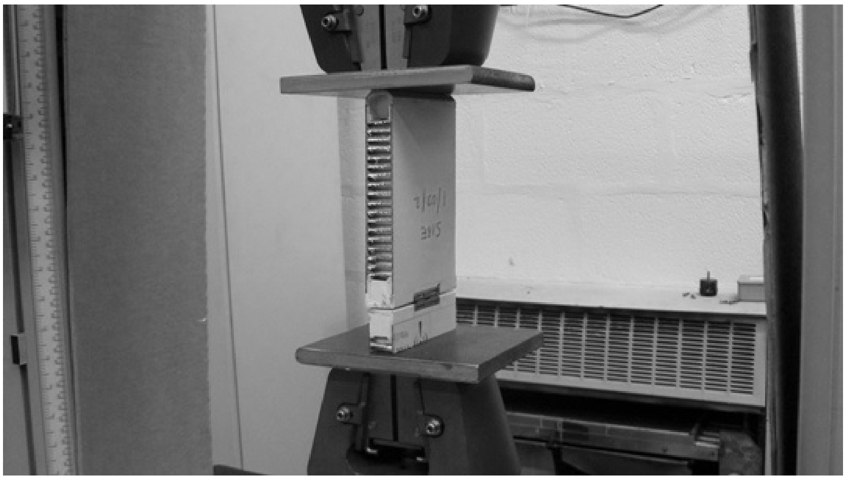


Fig. 6. Typical test specimens and setups
Rys. 6. Przykład przeprowadzanego testu

2.1.2. Pendulum Impact Tests

Impact pendulum tests provided an in-situ loading condition that cannot be replicated using quasi-static loading that is mentioned in Section 2.1.1.

2.1.2.1. Equipment

Below is the list of equipment used:

- IST Data Recorder (used for tri-axial acceleration recording);
- A pendulum system with an equivalent mass of 39.6 kg and a swinging arm of 1.33 m having an impact face of 300 mm (length) by 200 mm (width);
- Variable angle spirit level for the measurement of the angle of inclination of the pendulum rod;
- Overhead crane to lift the pendulum to the desired angle;
- High speed Sony camera (200 frames per second);
- Digital camera (for taking still pictures).

2.1.2.2. Test Set up

The table top is made up of an aluminium honeycomb core sandwiched between Formica laminates. The table is trimmed all way round with a thermoplastic edge, which makes contact with the pendulum impact face that represents the occupant's chest or abdomen in case of a crash. Impact characteristics of the bay table were measured by allowing a rigid steel pendulum weighing 39.6 kg to strike the flap edge of a TGV train bay table at 4.9 m/s. This gives impact energy of 475 J, approximately equivalent to that produced by a body block. A body block is a rubber and wooden construction of a human upper body part (chest, abdomen, neck and head). It weighs 36.9 kg [7].

Three tables were used for the tests. One was a First Class TGV train folding table (Test SIBE6/1), while the other two were similar but Standard Class TGV tables, which were smaller dimensionally (Test ID SIBE 6/2 and SIBE 6/2), respectively. Using a 39.6kg pendulum mass, the specimens were impacted by the load.

2.1.2.3. Test Procedure

In all cases, the table top was impacted on the edge using a rigid metal pendulum as shown in Fig. 7 below. For the first two tests (SIBE 6/1 and SIBE6/2), the inner flap (close to the side fixing) was impacted, while the outer flap was impacted in the third test (SIBE 6/3).

Fig. 7. Test Configuration (First Class TGV Table)
Rys. 7. Konfiguracja testowa (stół w wagonie pierwszej klasy pociągu TGV)

The impacting surface has an area of 300mm x 200mm. The measurements were based on the torso width of a body block [7]. An IST® data recorder was fitted to the back of the pendulum mass to capture acceleration at a sampling rate of 2000Hz. Upon downloading the recorded data, DynaMax® was used to post-process and analyse the data. The Butterworth filter was applied to the recorded data at 300Hz. Values of acceleration and velocity change against time of the impulse were plotted. Video footage and still pictures were analysed to understand the failure mechanisms.

3. RESULTS AND DISCUSSION

3.1. Description of Results

3.1.1. Quasi-static tests of Components of the Bay Table

Upon loading the test specimen, the front plastic collapses, then its edges push the laminates sideward (see Fig. 8). Subsequently, de-bonding between the laminate and honeycomb core occurs, resulting in the final abrupt collapse. The composite had a yield and ultimate compressive strengths of 6.0MPa/7.2MPa, respectively. It was observed that during the test, the flap did not fold about the table hinge.

From the tests conducted, it was concluded that failure of the full composite is triggered by the collapse of the front (occupant impact part) plastic through the failure mechanism described earlier, with the Young's Modulus ranging from 1GPa to 1.2GPa. The ultimate strength of the flap under quasi-static loading is 7.2MPa.

The maximum load for this test with a width of 100mm and thickness of 22mm was 15.8kN. As such, the maximum load for a width of 300mm (equivalent to a body block impact width) would be 47.6kN, - a loading far higher than the 0.5kN to 6kN range for injury tolerance of abdominal organs [8,9] and 8kN tolerance of the chest [9]. This implies that the occupant is far weaker than table edge. In the event of an impact, it is expected that the occupant could suffer fatal injuries.

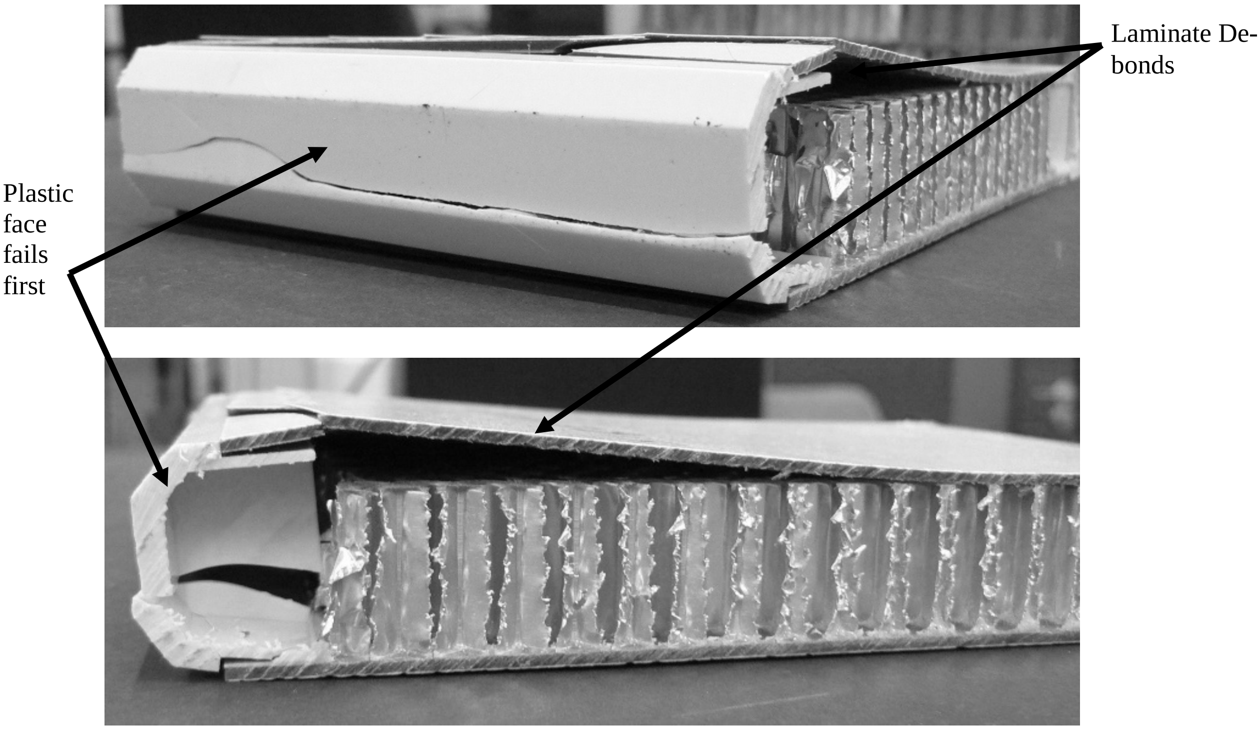


Fig. 8. Failure (mechanism) of the Complete Composite structure
Fig. 8. Uszkodzenie (mechanizm) kompletnej struktury kompozytu

3.1.2. Pendulum Impact Tests

3.1.2.1. Recorded Data and Analysis

This section presents the graphs of the pulse captured by the accelerometer. Further, it shows images revealing the failed parts of the table. Each sub-section has comments to explain the failure mechanism of the respective table.

3.1.2.1.1. First Class Table (SIBE 6/1) Impact Arm of 350 mm from the Side Fixing

For the First Class table design, the impulse lasted for 10 ms, and the corresponding velocity change was 3.56 m/s. Fig. 9 shows the load curve as a function of time. Fig. 10 shows the frame from the video footage just after the pendulum struck the table. Soon after, the Formica top moved upwards (de-bonding). This failure mechanism is similar to the one observed during quasi-static tests of the table parts (see Section 3.1.1).

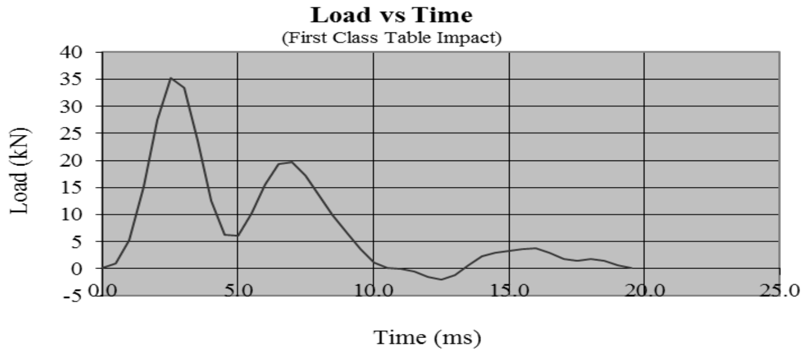


Fig. 9. Impact Characteristics of the TGV First Class
Rys. 9. Charakterystyka obciążenia w czasie dla wagonu pierwszej klasy pociągu TGV

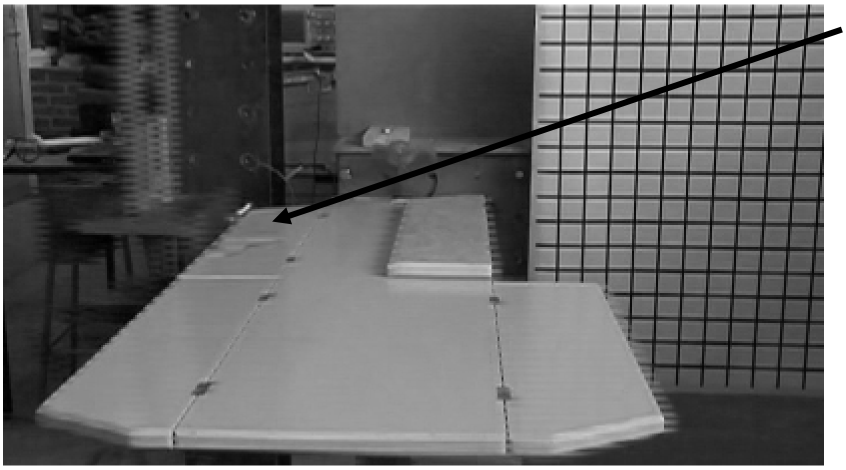


Fig. 10. Image Captured from First Class Test Video
Rys. 10. Zdjęcie zrobione podczas testu wideo pierwszej klasy

3.1.2.1.2. Standard Class Table 1 – Impact Arm at 350 mm from Side Fixing (SIBE 6/2)

For this first Standard Class table design, the impulse lasted for 3ms, and the corresponding velocity change was 1.32 m/s. Fig. 11 shows the load and energy curves as a function of time. Upon impact, the aluminium side fixing webs sheared off, resulting in the table falling while hinged about the floor fixing. Subsequently, both the floor plate and the bolt on the side of impact collapsed under tension. Hence the table fell as shown in Fig. 12. The impacted flap remained intact.

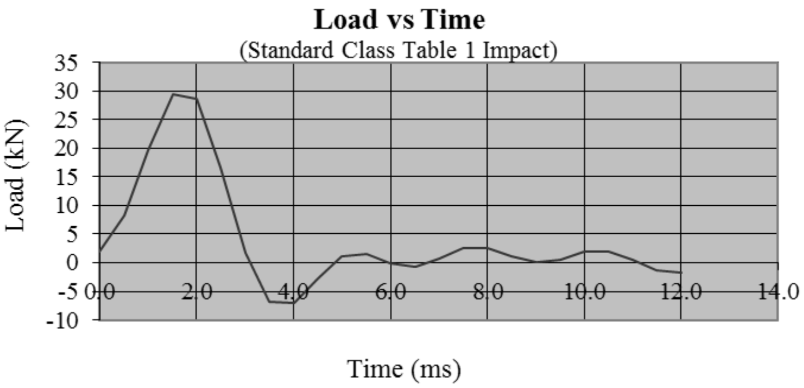


Fig. 11. Load Impact Characteristics of the TGV Second Class Table 1
Rys. 11. Charakterystyka obciążenia w czasie dla stołu 1 dla wagonu TGV drugiej klasy

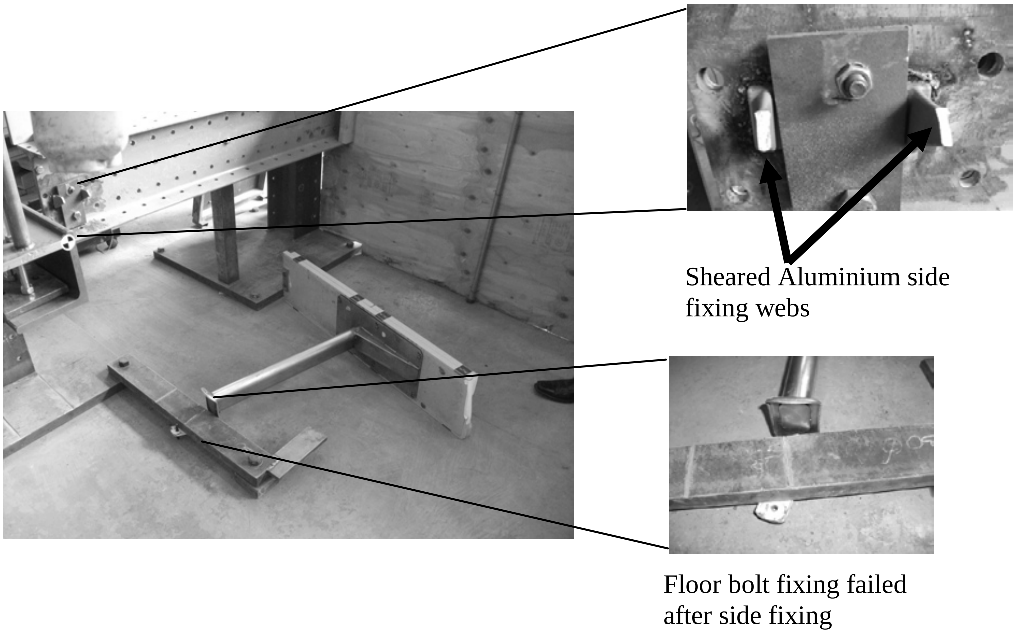


Fig. 12. Still pictures after impact
Rys. 12. Obrazy po uderzeniu

3.1.2.1.3. Standard Class Table 2 – Impact Arm at 800mm from the Side Fixing (SIBE 6/3)

For the Standard Class design Table 2 design, the impulse lasted for about 3ms, and the corresponding velocity change was 1.21 m/s. Fig. 13 shows the load curve as a function of time. Soon after the pendulum struck the table, the Formica top moved upwards (debonding). Further examination showed that the front plastic edge failed first. The plastic then pushed the laminate outwards, causing it to debond (which is similar failure mechanism observed during quasi-static tests).

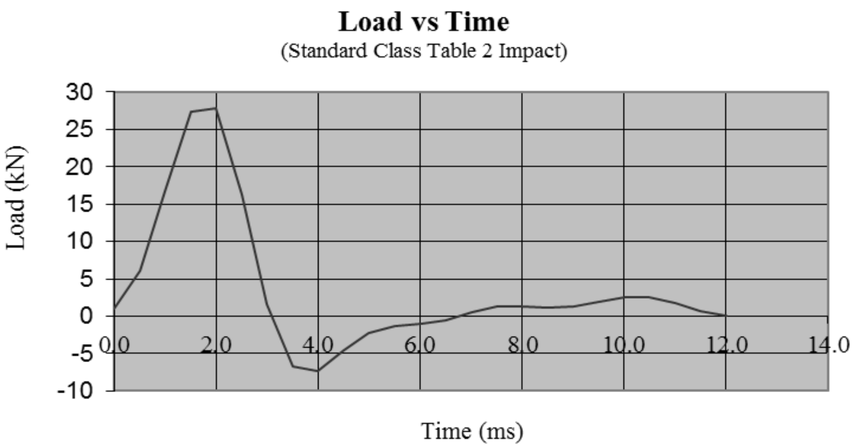


Fig. 13. Impact Characteristics of the TGV Second Class Table 2
Rys. 13. Charakterystyka obciążenia w czasie dla stołu 2 w wagonie TGV klasy drugiej

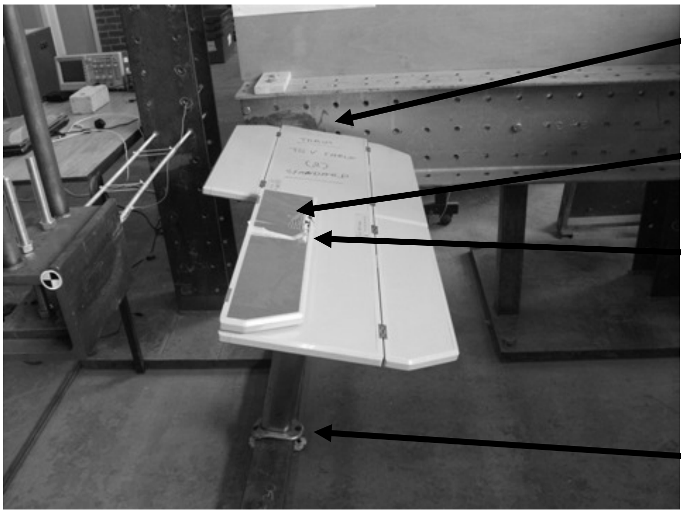


Fig. 14. Still Picture of Failed Table 2
Rys. 14. Obraz uszkodzenia stołu 2

3.1.2.1.4. Boundary Conditions – Loading

Table 1 shows the recorded parameters (velocity and deceleration) and calculated values (energy and loading).

Table 1

Table Impact Loading

Test ID	Impact Velocity (m/s)	Velocity Change (m/s)	Maximum Deceleration (g)	Initial Impact Energy (J)	Absorbed Impact Energy (J)	Average Impact Loading (kN)	Maximum Loading (kN)
SIBE 6/1	4.9	3.56	90.82	475	440	14.1	35.3
SIBE 6/2	4.9	1.32	75.83	475	222	17.4	29.5
SIBE 6/3	4.9	1.21	70.54	475	206	16.0	27.4

The above results reveal that for the First Class table impact test (SIBE 6/1), a maximum of 35.3 kN loading was attained, and most of the loading was absorbed in the actual failure of the table rather than the side or floor fixing. By contrast for the Standard Class tables the maximum loading was about 29.5 kN and 27.4 kN for the two tests (SIBE 6/2 and SIBE 6/3, respectively), with much less energy absorbed because major failure was observed in the side and floor fixings. Examination of the impacted tables and video footage showed that energy was absorbed through the following means:

1. Actual failure of the impacted table flap
2. Failure of the table top middle fixed part (First Class Tables)
3. Side fixing (Second Class/Standard Tables)
4. Floor fixing (Second Class/Standard Tables)
5. Vibrations

3.1.2.1.5. Remarks

From the impact tests of the three tables, the maximum loads generated by the table ranged from 27 kN to 35 kN, and the mean loads varied from 14 kN to 17 kN. These loadings are far higher than the 0.5 kN to 6 kN range for injury tolerance of abdominal organs [8, 9] and 8 kN tolerance of the chest [9]. While it is acknowledged that the tables ought to have structural strength to improve durability and minimise vandalism, it is also important to ensure that they do not pose a safety hazard to occupants in the event of a crash. Based on the impact results, it is concluded that the tables are overly impact-aggressive. From the tests, some tables detached upon impact, while some did not. This confirms the real accident data from accidents such as what happened during the UK Suffolk train-truck collision in 2010. The deformation of the table pedestals (or legs) is a similar phenomenon to that observed during the train collision in Suffolk.

3.2. Bay Table Failure Behaviour

Both quasi-static and dynamic tests have shown that in the event of an occupant colliding with a bay table, the tested tables have a capability of developing resistive forces ranging from 27.4 kN to 47.6 kN. Such loading is far higher than the 0.5 kN to 6 kN range for injury tolerance of abdominal organs and 8 kN tolerance of the chest. Fig. 15 shows the comparison. The resistive forces may not be justifiable even though railway vehicle standards require a minimum resistive horizontal load of 1.5 kN [6].

As depicted in Fig. 16, an ideal table should be so engineered that it meets its functional requirements and have the capability to withstand service loads without compromising impact safety.

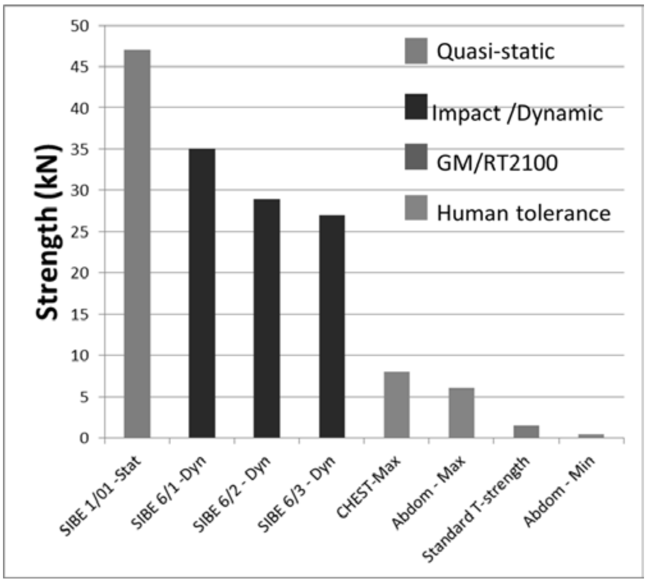


Fig. 15. Table Strength vs Human Tolerance
Rys. 15. Zestawienie siły z ludzką tolerancją

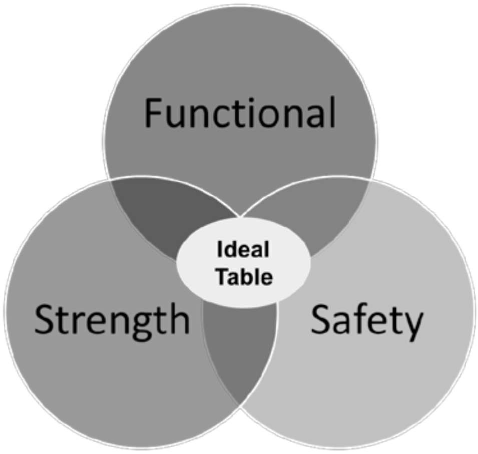


Fig. 16. Ideal table
Rys. 16. Idealny stół

4. CONCLUSIONS

A methodological approach has been developed that helps to determine the table aggression on an occupant's thorax and how that relates to human injury tolerance. When considering the impact loading of a table on an occupant, the combined effect of the strength of the side fixing, pedestal and impact surface should be taken into account.

Research results presented in this paper indicate that a typical bay table is overly impact aggressive during occupant secondary collision. Current design of typical bay tables focusses mainly on functional and structural design. Although safety is considered in the design, it is aimed at meeting static loading requirements as opposed to any dynamic loading that may be induced through secondary collision of an occupant during a crash.

5. FUTURE WORK

Future research will involve computer numerical modelling of different loading conditions on the table. The experimental results presented in this paper would serve as a basis for validating the model. Additional research is needed in design of tables that are optimised for crash safety without jeopardising functionality and strength. This is critical particularly that installation of tables could not only be a desirable furniture for use to place items, but also as an occupant displacement 'interceptor' to minimise the distance through which the occupant travels. Limiting this distance also minimises the kinetic energy carried by the occupant during collision. The higher the kinetic energy at collision, the higher is the injury potential.

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