

Exploring the frangibility of steel circular hollow section small sign support posts

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Key Findings

- Guidance to practitioners on frangible small sign support posts varies between jurisdictions.
- Australian/New Zealand Standard AS/NZS 3845.2:2017 prescribes a definitive testing protocol to establish frangibility.
- The largest steel section that is expected to meet the requirements of Australian/New Zealand Standard AS/NZS 3845.2:2017 for a small sign support is a 76.1 mm OD x 3.2 mm Grade 350 CHS.

Abstract

Desirably sign support posts should be frangible if not shielded. Review of technical governance in the Australian/New Zealand context suggests that guidance to practitioners on what is frangible varies between jurisdictions. Australian/New Zealand Standard AS/NZS 3845.2:2017 prescribes test requirements for frangibility. This study uses results from full-scale crash testing combined with theoretical analysis to explore the expected crash performance of circular hollow section (CHS) sign supports. The study recommends the CHS sign support that is expected to represent an upper threshold of frangibility that would satisfy the provisions of Australian/New Zealand Standard AS/NZS 3845.2:2017.

Keywords

Frangibility, Crash testing, Sign support posts

Introduction

Australian Standard AS 1742.2:2009 (Standards Australia, 2009) prescribes (in terms of nominal bore and wall thickness) the sizes of grade C350 steel circular hollow section small sign support posts that are regarded as frangible. However, jurisdictional practice for small sign supports in Australia and New Zealand varies, as is documented in Table 1.

In the interests of informed and harmonised technical governance, objective evidence of what constitutes a “frangible” small sign support post is required, as recommended by McInerney et al (2002). Usefully, the recently published Australian/New Zealand Standard AS/NZS 3845.2:2017 (2017) provides a definitive testing protocol. The scope of section 9 of AS/NZS 3845.2:2017 includes that a “...*sign support structure or pole is to be frangible, readily activated in a predictable manner by breaking away, fracturing or yielding*”. The concept of frangibility is then introduced as a failure mechanism of a breakaway (sign) support structure, and a test matrix is established for this classification of objects.

Consistent with European Normative EN 12767 (European Committee for Standardization, 2007), which prescribes a test impact by a passenger car with a test inertial mass of 825

kg impacting at 35 km/h, AS/NZS 3845.2:2017 requires that frangible sign supports meet prescribed occupant risk criteria when subjected to an impact by an 1100 kg car travelling at 30 km/h. This lower speed (lower energy) test is described in the Standard as being designed to evaluate kinetic energy to activate the frangible mechanism. Occupant risk criteria to be met are specified in Table 5.1 of the Manual for Assessing Safety Hardware (MASH) (American Association of State Highway and Transportation Officials (AASHTO), 2009). Thresholds of occupant risk exist in terms of the flail space indicators (OIV and ORA), but also in terms of occupant compartment intrusion/deformation.

Additionally, the full test matrix for frangibility of a sign support post to be (for example) 100 km/h rated requires testing with a light car (1100 kg) and a heavy utility (2270 kg) at 100 km/h and evaluation of, among other things, detached elements, vehicle trajectory and occupant risk. The important point to note is that for an object to be rated “frangible” speeds of 100 km/h, it needs to be tested at both 100 km/h and 30 km/h.

Consequently, a low energy test (1100 kg car travelling at 30 km/h) is required regardless of the speed for which the sign support is to be rated, which may be considered

Table 1. Examples of variations in jurisdictional practice for small sign support posts^a

Speed (km/h) ^b	AS 1742.2 ^c	NSW ^d	NZ ^e	QLD ^f	SA ^g	VIC ^{h, l}	WA ^{i, m}
<60	90 NB x 2.6			100 NB x 3.6			101.6 OD x 2.6
60 to 80	65 NB x 2.3	88.9 OD x 3.2 ^j	76 OD x 3.2	80 NB x 3.2	Footnote k	50 NB or less ^l	76.1 OD x 2.3
>80	50 NB x 2.9			65 NB x 3.2			60.3 OD x 2.9

Footnotes

- Some jurisdictional governance references post sizes in terms of Nominal Bore (NB) whereas some governance uses Outside Diameter (OD). This is a practice inconsistency that might benefit from harmonized approach.
- Speed can mean “likely collision speed”, “posted speed” and/or “speed zone”, depending on jurisdiction.
- Manual of Uniform Traffic Control Devices: Traffic control devices for general use (Standards Australia, 2009).
- Installation and maintenance of signs (New South Wales Roads and Traffic Authority, 2010).
- Specification TNZ P/24 (New Zealand Transport Agency, 2008) and associated industry guide (Road Safety Manufacturers’ Association, 2008).
- Design Guide for Roadside Signs (Queensland Department of Transport and Main Roads, 2001).
- DPTI Specification Part R49 Installation of signs (South Australia DPTI, 2016).
- Supplement to AS 1742.2:2009 (VicRoads, 2015).
- Large Multiple Post Signs – Sign Structural Design (Main Roads WA, 2015).
- NSW document identifies a grade C350 steel section equivalent to 88.9 OD x 4.0 Grade C250 CHS.
- DPTI South Australia specification R49 requires RHS for small sign supports and states “Circular Hollow Sections must not be used for small to medium size signs under any circumstances”. For larger signs, the document prescribes section sizes deemed to be frangible as a function of speed zone (km/h). For a speed zone ≤ 60 km/h, an 80 NB x 5.0 or 100 NB x 3.5 Grade C350 is deemed frangible.
- VicRoads’ document (VicRoads, 2015) states: “Posts of 50 mm nom. bore or less are not breakaway types, but are considered light enough to present a minimal hazard to out-of-control vehicles”.
- Note that the guidance from Main Roads WA is for multiple sign support posts.

inconsistent with what Australian Standard AS 1742.2:2009 presents (see Table 1) as “frangible”, which is larger posts at lower speeds. In this regard it might be conjectured that Australian Standard AS 1742.2:2009 may have intended that larger posts would present reduced likelihood of adverse consequence if impacted at lower speeds, perhaps implying that the interpretation of “frangible” in Australian Standard AS 1742.2 is different to what is intended in Australian/New Zealand Standard AS/NZS 3845.2. This inconsistency attracts the need for clarification.

Objective

Ross et al (1989) propose a “*methodology for estimating velocity change in small sign support impacts for small vehicles based on test results of other vehicles*”. The methodology assumes (with caveats) that energy loss is independent of vehicle mass, and that vehicular velocity change for a small vehicle mass can be estimated based on energy lost measured during crash testing using a larger vehicle. The same premise is employed in this study.

The central hypothesis here is that a given sign support section might represent a level of resistance to deformation requiring a quantum of energy to precipitate displacement or deformation. Further, it is expected that the energy requirement would be a function of the sectional properties of the sign support post.

The broad aim is to present a preliminary exploration of the aggressiveness (or resistance to failure) of single circular hollow section sign supports when subjected to vehicular impact with the intent to inform future work in this area. The primary objective is to use a combination of full-scale crash testing combined with theoretical analysis in the context of testing conducted by others in order to predict the largest post (in terms of sectional properties) that would be expected to satisfy the critical low-energy test requirements of AS/NZS 3845.2 (2017).

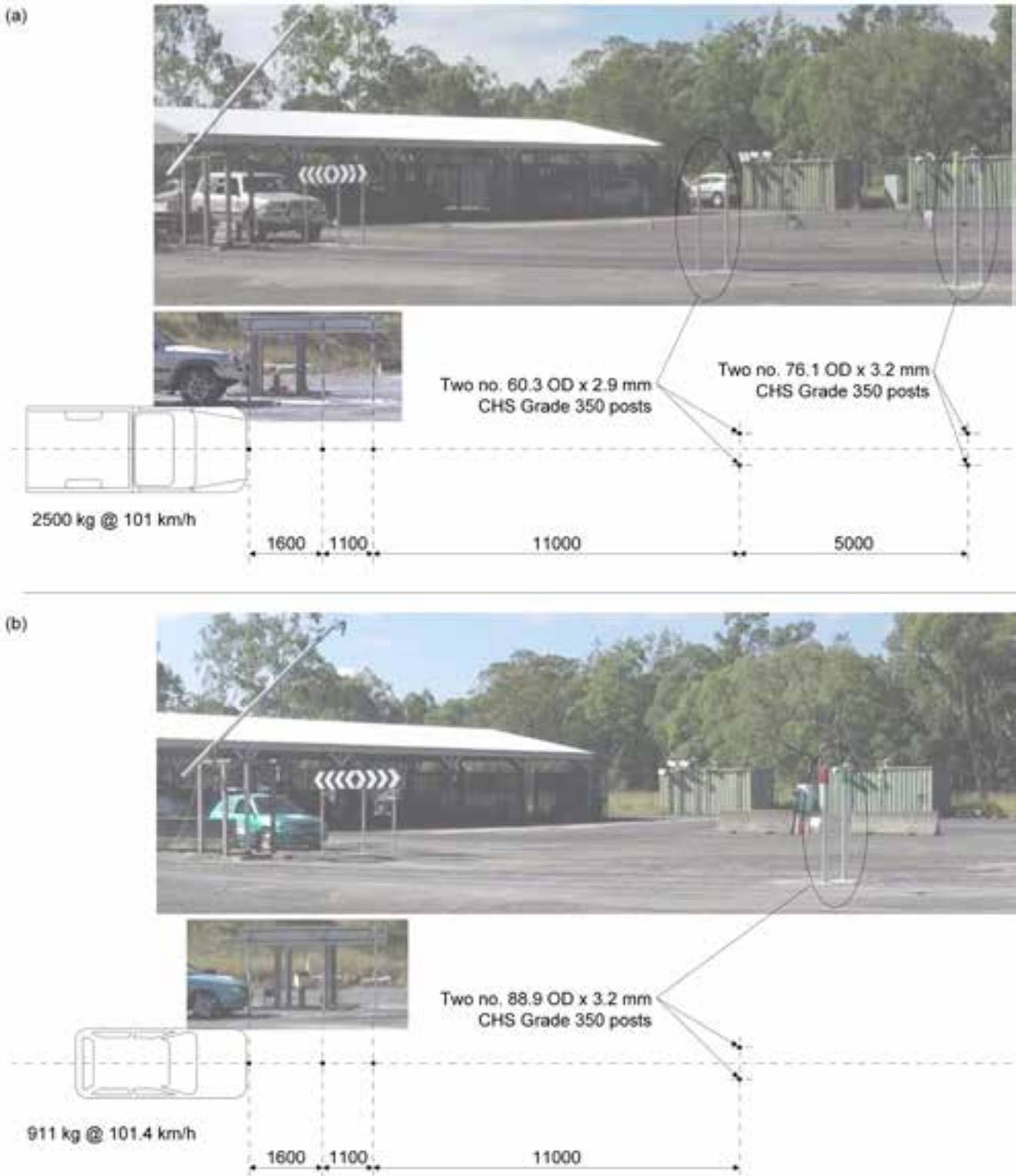


Figure 1. Number of injury hospitalisations and percentage of hospitalised serious injuries of pedestrians, pedal cyclists and motorcyclists in NSW hospitalisation-mortality linked data, 1 January 2010 to 30 December 2013

Methodology

Background

Muthubandara et al. (2017) present an evaluation of treatments of multi-post road intersection hazard-board signs to mitigate risk of windscreen penetration in end-on impacts. A series of ten full-scale crash tests were conducted. Initial intentions were to utilise the same crash test data to derive some knowledge of the aggressiveness of different CHS sections when impacted. However during the evolution of the testing program it became apparent that the resistance to failure of the posts could not be confidently discerned from the testing of the sign configuration as the structure of the sign itself and its fixings to the posts appeared to influence the resistance to deformation of the system. As such, the testing program was subsequently modified to include standalone posts. Two tests, which are the focus of this study, were conducted with standalone posts.

Crash testing

In these two tests, pairs of Grade 350 CHS posts were arranged symmetrically about the line of vehicle trajectory downstream of the multi-post road intersection sign being tested by others (Muthubandara, et al., 2017) with the intention that both posts in each pair would be impacted simultaneously. The configurations of the two test articles are depicted in Figure 1.

In the first test (ref. B17013) two pairs of posts each 700 mm apart were located respectively 13.7 m and 18.7 m downstream from the initial impact point with the multi-post road intersection sign. The first pair of posts were 60.3 mm OD x 2.9 mm CHS Grade 350 and the second pair were 76.1 mm OD x 3.2 CHS Grade 350. A separation distance of 5.0 m was considered sufficient for the effects of the impacted article on the vehicle to have been completed. The 11.0 m separation between the multi-post sign and the first pair of posts was for the convenience of the test-house. This test configuration is depicted in panel (a) of Figure 1.

In the second test (ref. B17018), a single pair of 88.9 mm OD x 3.2 mm CHS Grade 350 posts was placed symmetrically (600 mm apart) about the projected vehicle trajectory, 11.0 m downstream of the multi-post road intersection sign test article. This test configuration is depicted in panel (b) of Figure 1.

For test ref. B17013 the impacting vehicle was a 1998 Nissan Patrol SUV with inertial mass of 2500 kg and initial impact speed 101.0 km/h. It is noted that the test vehicle was equipped with a bull-bar. For test ref. B17018 the impacting vehicle was a 1996 Daihatsu Charade Hatchback with inertial mass of 911 kg and initial impact speed of 101.4 km/h.

Analysis

For each test, longitudinal vehicular acceleration (CFC180) was recorded at a frequency of 20000 Hz. Mean acceleration

across each time increment was used to compute the longitudinal change in the velocity of the impacting vehicle across the same time increment (Equation 1). The velocity of the vehicle after each time increment was determined by aggregating the initial impact velocity and the summation of the velocity changes across each time increment (Equation 2). Displacement (of the accelerometer on-board the impacting vehicle) during each time increment was then calculated as a product of the time increment and the average velocity across it (Equation 3). Total displacement was then computed as the summation of the preceding displacements (Equation 4).

$$\Delta v_i = \frac{1}{2}(a_i + a_{i-1})(t_i - t_{i-1}) \quad (1)$$

$$v_i = v_0 + \sum_{i=1}^i \Delta v_i \quad (2)$$

$$\Delta d_i = \frac{1}{2}(v_i + v_{i-1})(t_i - t_{i-1}) \quad (3)$$

$$d_i = \sum_{i=1}^i \Delta d_i \quad (4)$$

where

a_i = longitudinal acceleration (CFC180)(m/s²) of test vehicle after time increment i .

t_i = time elapsed (s) after time increment i .

v_i = longitudinal velocity (m/s) of test vehicle after time increment i .

d_i = longitudinal displacement (m) of test vehicle after time increment i .

The resulting data was used to calculate kinetic energy change throughout the test article. As far as possible, 5 metres beyond the test article was adopted as the point at which interaction with the test article was deemed complete, in order to be consistent with similar testing undertaken by Savin (2003).

Results

Test B17013

Having impacted the upstream hazard-board assembly (which is not part of this study) the test vehicle impacted the pair of 60.3 mm OD x 2.9 mm posts at a computed 10 ms average velocity of 25.84 m/s. The video footage suggests that the impact was approximately symmetrical and simultaneous. These posts yielded at the base, folding forwards as the test vehicle passed over the top. The test vehicle then impacted the pair of 76.1 mm OD x 3.2 mm posts at a computed 10 ms average velocity of 25.43 m/s. While the video footage suggests that the left side post was impacted slightly earlier than the right side post was impacted, possibly due to asymmetrical bumper deformation, both posts were observed to fail similarly, yielding at the base, and folding forwards while the test

vehicle passed over the top. It is observed that some components of the upstream hazard-board assembly remained in contact with the test vehicle throughout the duration of both subsequent freestanding post impacts. The velocity of the test vehicle at 5 m downstream of the test article was computed as 24.78 m/s.

Figure 2 shows longitudinal acceleration and velocity (m/s) plotted against both time and horizontal displacement for the vehicle in test ref. B17013. Key observations are summarised in Table 2. This data indicates a velocity change while yielding two 60.3 mm OD x 2.9 mm posts of 0.42 m/s, representing a change in kinetic energy of 26.67 kJ, or 13.3 kJ per post. Likewise the data indicates a velocity change while yielding two 76.1 mm OD x 3.2 mm posts of 0.65 m/s, representing a change in kinetic energy of 40.80 kJ, or 20.4 kJ per post. This is summarised in Table 3.

Test B17018

The test vehicle was observed to become airborne due to impact with the upstream hazard-board assembly, and did not land “true” being rotated slightly towards the left. The

impact velocity with the pair of 88.9 mm OD x 3.2 mm posts based on distance travelled in the longitudinal direction was computed as 17.39 m/s. The left side post was impacted more or less at the centreline of the test vehicle while the right side post appears to have missed being impacted by any structural elements of the vehicle chassis, and being impacted by the front-right wheel and suspension assembly. While the impact was not as clean as intended, both posts were observed to fail similarly, yielding at the base, and folding forwards while the test vehicle passed over the top. The velocity of the test vehicle at 3.2 m downstream of the test article was computed as 11.96 m/s.

Figure 3 shows longitudinal acceleration and velocity (m/s) plotted against both time and horizontal displacement for the vehicle in test ref. B17018. Key observations are summarised in Table 4. This data indicates a velocity change while yielding two 88.9 mm OD x 3.2 mm posts of 5.43 m/s, representing a change in kinetic energy of 72.6 kJ, or 36.3 kJ per post. This is summarised in Table 5.

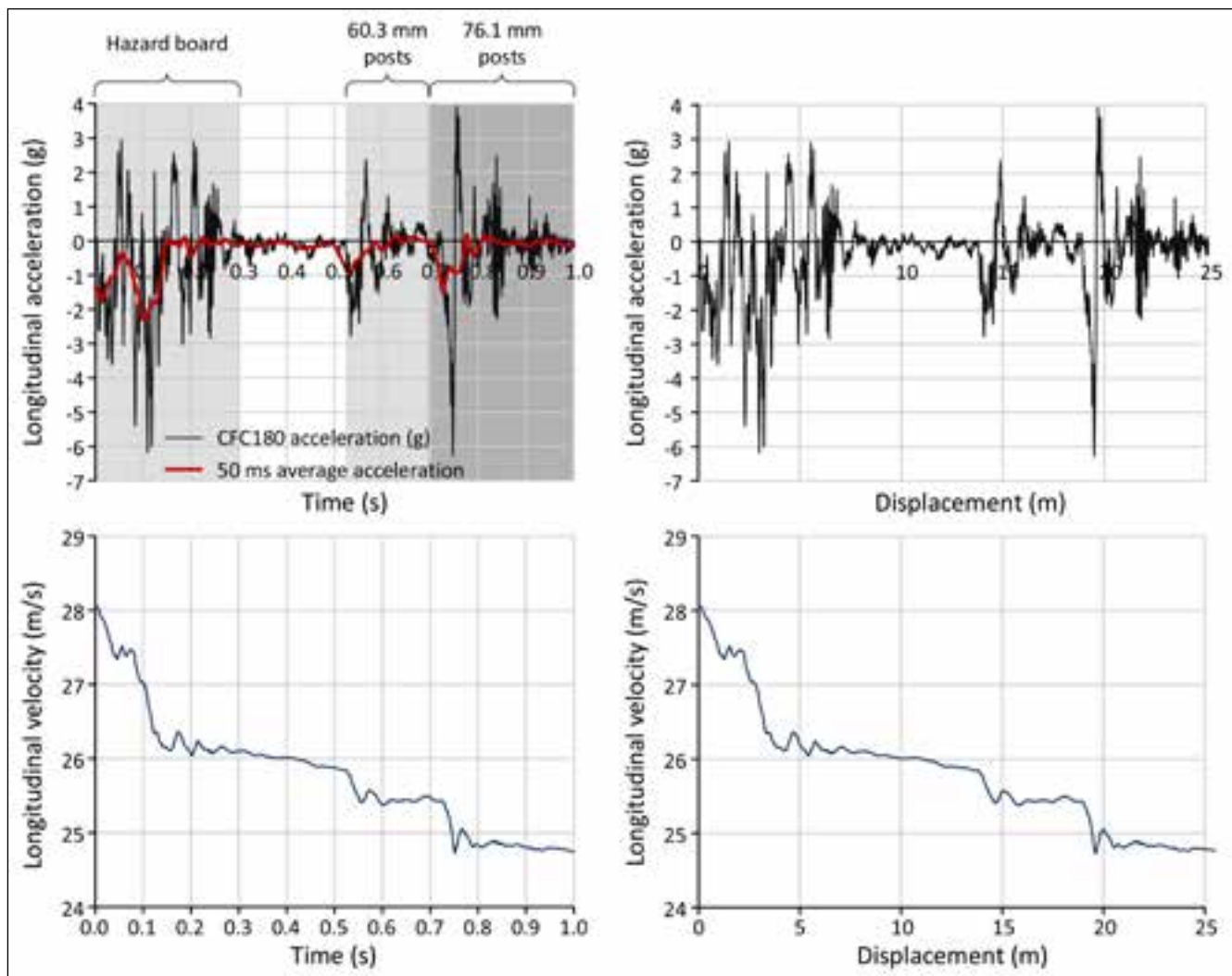


Figure 2. B17013 test data

Table 2. Key observations from Test B17013

Impact Point	Distance (m)	Time (ms)	Ave 10 ms velocity (m/s)	ΔV (m/s)	Ave 10 ms Energy (kJ)	ΔE (kJ)
HB_Post 1	0.00	0.00	28.06	-	983.89	-
HB_Post 2	1.60	57.85	27.46	0.59	942.85	41.04
HB_Post 3	2.70	98.10	27.03	0.44	913.13	29.72
HB_Post 3 + 5m	7.70	288.65	26.09	0.94	850.59	62.54
60.3 OD x 2	13.70	519.55	25.84	0.24	834.91	15.68
76.1 OD x 2	18.70	715.70	25.43	0.42	808.24	26.67
76.1 OD + 5 m	23.70	916.35	24.78	0.65	767.42	40.82

Table 3. Summary of key observations from test B17013

	Distance (m)	Time (ms)	ΔV (m/s)	ΔV (m/s) (per post)	ΔE (kJ)	ΔE (kJ)(per post)	Peak 50 ms accn (g)
Sign (3 posts)	0.00 – 7.70	288.65	1.97	0.66	133.30	-	-2.29
60.3 OD x 2	13.70-18.70	196.20	0.42	0.21	26.67	13.3	-0.93
76.1 OD x 2	18.70-23.70	200.60	0.65	0.33	40.82	20.4	-1.50

Analysis and discussion

Three data points, being the energy loss for each of three circular hollow sections when impacted, are the primary focus of this study.

This data is considered and discussed in the context of research by others (Savin, 2003), who reports on three full scale test impacts into circular hollow section sign support posts. Savin's results are reproduced in summary here at Table 6.

Sectional properties for the posts tested by Savin (2003), combined with similar data recorded in this study, are provided at Table 7 and presented in Figure 4

By method of least squares regression, a simple power function of best fit to the data is given by Equation 5.

$$\Delta E = 72.847 \times I^{1.309} \quad (5)$$

Australian/New Zealand Standard AS/NZS 3845.2 (2017) defines the requirements for frangibility for a breakaway sign support. The critical occupant test is an 1100 kg vehicle impacting at 30 km/h (8.33 m/s). The evaluation criteria include that the Occupant Impact Velocity (OIV) should preferably not exceed 3.0 m/s and must not exceed 4.9 m/s. Hence, on the basis that vehicular velocity change occurs only during the impact, the OIV criterion indicates an upper threshold of velocity change of 4.9 m/s. The kinetic energy of the critical occupant test is 38.19 kJ. In order that the velocity change through the impact does not exceed 4.9 m/s, the residual velocity of the test vehicle after impact would need to be 3.43 m/s (8.33 m/s minus 4.9 m/s), which represents a kinetic energy of 6.48 kJ. So the maximum permissible kinetic energy loss is 31.69 kJ.

Use of Equation 5 would suggest that the permissible maximum kinetic energy loss of 31.69 kJ would be produced by a section with Moment of Inertia $0.529 \times 10^6 \text{ mm}^4$. With reference to standard section sizes under Australian/New Zealand Standard AS/NZS 1163 (Standards Australia, 2016) the largest circular hollow section with Moment of Inertia less than $0.529 \times 10^6 \text{ mm}^4$ is a 76.1 mm OD x 3.2 mm ($I = 0.488 \times 10^6 \text{ mm}^4$). It may be that a 38.19 kJ impact is sufficient energy to deform/displace a larger section (for example 76.1 mm OD x 3.6 mm; $I = 0.540 \times 10^6 \text{ mm}^4$), but the evidence suggests that the occupant injury criteria (OIV $\leq 4.9 \text{ m/s}$) of the crash test may be exceeded by that section in the low energy test.

Of course, there are obvious difficulties in being definitive from such limited data. For example, an immediate observation is that Savin (2003) conducted two tests on an 88.9 mm OD x 4.0 mm post both with a light vehicle (~840 kg) but travelling at different speeds, and obtained very different results in terms of kinetic energy loss. In the 102 km/h test, the computed kinetic energy change based on velocity is 119.5 kJ, whereas in a test at 35 km/h, the vehicle came to rest 4.6 m downstream of the test article, recording a kinetic energy loss of 39.7 kJ. Both of these data points are included in this analysis. However it is possible that if the initial energy of the low speed test were increased, the vehicle may still have been arrested and so a higher energy loss would have been recorded.

A second observation is that the test articles and test vehicles differ. Specifically, test B17013 of this study was conducted with a large vehicle equipped with a bull-bar, while the test vehicle used in test B17018 was a small vehicle without a bull-bar. It is possible that stiffness of the test vehicles as well as any pre-impact damage may have influenced the outcomes.

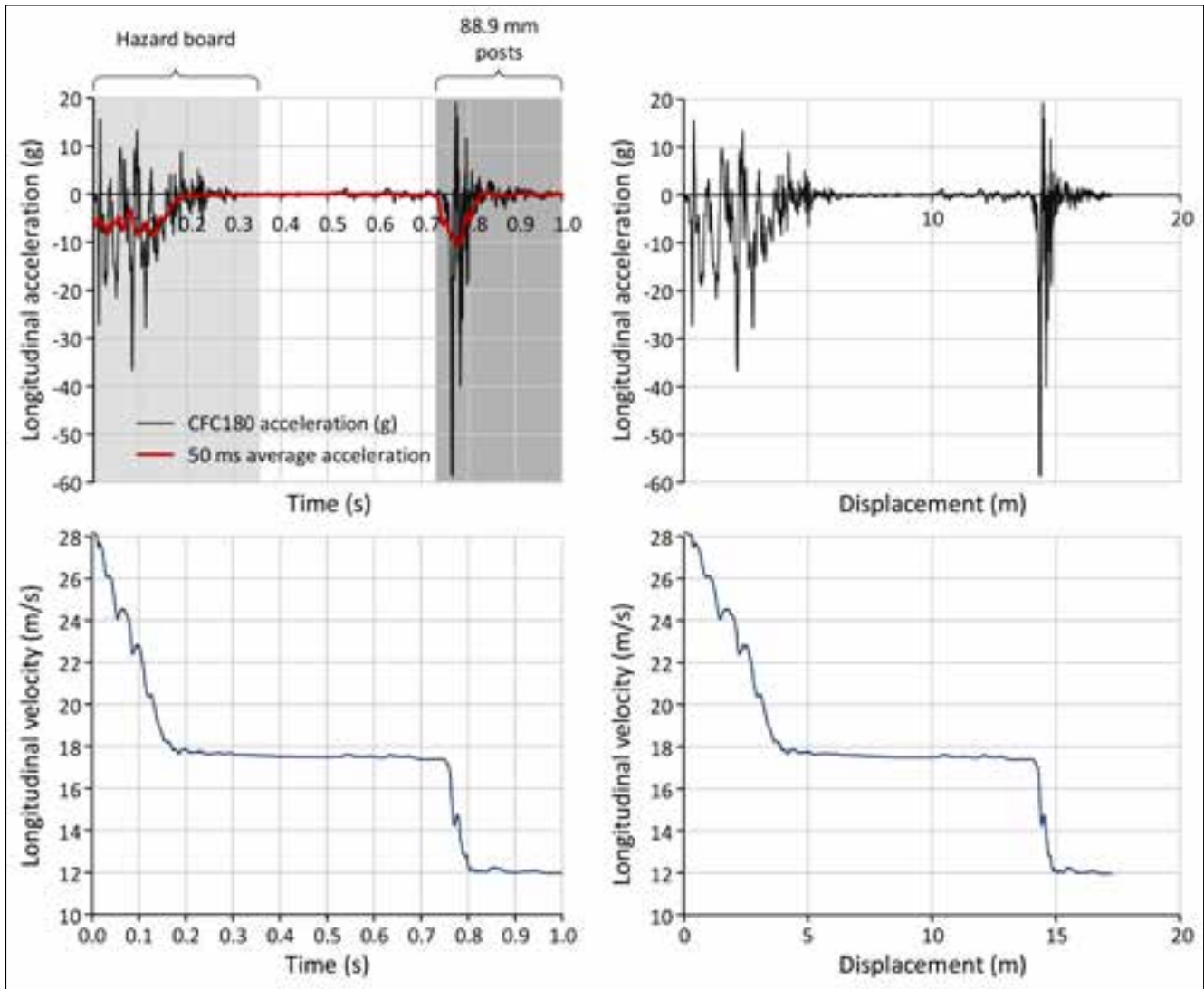


Figure 3. B17018 test data

Table 4. Key observations from Test B17018

Impact Point	Distance (m)	Time (ms)	Ave 10 ms velocity (m/s)	ΔV (m/s)	Ave 10 ms Energy (kJ)	ΔE (kJ)
Post 1	0.00	0.00	28.17	-	361.45	-
Post 2	1.60	60.65	24.39	3.78	270.94	90.51
Post 3	2.70	107.65	21.99	2.40	220.36	50.58
Post 3 + 5m	7.70	384.40	17.54	4.45	140.12	80.24
88.9 OD x 2	13.70	727.30	17.39	0.15	137.77	2.35
88.9 OD + 3.2 m*	17.00	979.80	11.96	5.43	65.20	72.57

Table 5. Summary of key observations from test B17018

	Distance (m)	Time (ms)	ΔV (m/s)	ΔV (m/s) (per post)	ΔE (kJ)	ΔE (kJ) (per post)	Peak 50 ms accn (g)
Sign (3 posts)	0.00 - 7.70	384.40	10.63	3.5	221.33	-	-8.89
2 x 88.9 x 3.2	13.70 - 17.00	269.20	5.43	2.7	72.57	36.3	-10.45

Table 6. Results from Savin (2003)

Post size	88.9 mm OD x 4.0	114.3 mm OD x 5.0	88.9 mm OD x 4.0
Inertial mass (kg)	842	839	840
Impact speed (km/h)	102	102	35
Exit speed (km/h)	82	52	-
Delta-v (m/s)	5.6	13.9	9.7
Kinetic Energy change (kJ)	119.5	249.2	39.7

Table 7. Combined results

Test	Outside diameter (mm)	Wall thickness (mm)	Moment of Inertia (10 ⁶ mm ⁴)	Energy loss (kJ)
B17013	60.3	2.9	0.216	13.3
B17013	76.1	3.2	0.488	20.4
B17018	88.9	3.2	0.792	36.3
Savin (2003), 01	88.9	4.0	0.963	119.5
Savin (2003), 02	114.3	5.0	2.569	249.2
Savin (2003), 03	88.9	4.0	0.963	39.7

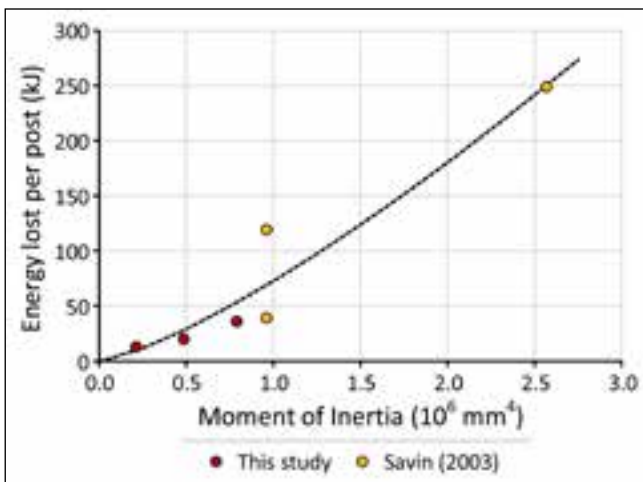


Figure 4. Energy lost per post (kJ) v CHS Moment of Inertia calculated from six crash tests

Further, test articles utilised in this study were in the order of 2 m tall with no sign attachments. The test articles used by Savin (2003) were continuous tube fitted with sign attachments typically measuring 2100 mm to the base of the sign. In the tests conducted by Savin (2003), the sign typically detaches from the top of the post, but the post yields forwards with the motion for the vehicle as observed in this study. For comparison, Bligh et al. (2017) presented analysis in terms of crashworthiness of a 73 mm OD x 3.4 mm pipe support fitted with a breakaway mechanism and conclude that signs with area 1.30 m² “as the minimum sign area applicable for all types of frangible sign support connections when the sign panel and support post are released from the base and rotate as a rigid body after vehicle impact”. It is noted that in the work presented by

Bligh, et al. (2017) the breakaway mechanism facilitates rotation of the test article so that the vehicle passes beneath the article, without causing critical occupant compartment deformation.

Hence, it is implicit that the height and size of the sign face may be expected to influence progression of the failure mechanism throughout the impact. Notably, the MASH test protocol does specify that for tests of a sign support system, the area of the sign panel should approximate the largest panel that would normally be used on the support system, and that the height-to-width ratio of the sign should be typical of the largest panel that would normally be used on the support system, mounting height of the sign panel (distance from ground to bottom of panel) should be the minimum height that the panel would normally be mounted in service.

No attempt has been made here to adjust for differences between test articles or test vehicles. That said, it is appropriate to recall that this study was opportunistic, leveraging off crash testing being conducted for another purpose, and is at best to be considered as research and development testing to inform a possible future test program. The data and discussion is provided here to inform such future work. In that context, the recommendation from this study is that a program of surrogate vehicle testing could be undertaken using a 76.1 mm OD x 3.2 mm Grade 350 CHS small sign support post fitted with a typical large face-area sign (~1 m²), to ensure both (i) that the assembly is not likely to present unacceptable occupant risk due to high accelerations in low energy impacts and (ii) that the assembly is not likely to present unacceptable risk in terms of detached elements, vehicle trajectory and occupant compartment intrusion/deformation. Should such

testing indicate likelihood of successful outcomes, full-scale compliance crash testing of the same circular hollow section and evaluation in accordance with the requirements of AS/NZS 3845.2 (Standards Australia, 2017) could be undertaken.

It should be noted that analysis of arrays of posts each of which individually may be frangible but which may not be frangible when in combination might usefully be the subject of further research. Additionally, it should also be noted that the standardised testing targets assessment of risk to only one road user group (i.e., occupants of light passenger vehicles) but makes no provision for assessment of risk to other road users, especially motorcyclists. Understanding how sign support posts that are considered frangible to light passenger vehicle occupants continue to present risk to vulnerable users and how such risk can be mitigated also attracts attention.

Conclusion

The objective was to present a preliminary exploration of the aggressiveness (or resistance to failure) of circular hollow section sign support posts when subjected to vehicular impact. This has been done, and results are presented.

Based on the results derived in this study, combined with the results from published literature, the circular hollow section sign support that is expected to represent an upper threshold of frangibility that would satisfy the requirements of AS/NZS3845.2 (Standards Australia, 2017) is a 76.1 mm OD x 3.2 mm Grade 350 CHS. The recommendation from this study is that a program of surrogate vehicle testing followed by full-scale compliance testing and evaluation of the same circular hollow section with a sign attachment is undertaken in accordance with the requirements of AS/NZS 3845.2 (Standards Australia, 2017).

To close, it is suggested that any such test program would include contingency to conduct testing on a different section size depending on the results of the initial testing.

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References

- American Association of State Highway and Transportation Officials (AASHTO). (2009). *Manual for assessing safety hardware (MASH)*. Washington, DC, USA: AASHTO.
- Bligh, R., Dobrovoly, C., & Harrington, D. (2017). *Development of guidance for minimum sign area for slipbase sign supports*. Paper presented at First International Roadside Safety Conference, San Francisco, CA, USA.
- European Committee for Standardization. (2007). *EN 12767 Passive safety support of structures for road equipment - Requirements, classification and test methods*. Brussels, Belgium: CEN.
- Main Roads WA. (2015). *Large multiple post signs - sign structural design*. Perth, WA, Australia.
- McInerney, R., Dunjey, M., & Grzebieta, R. (2002). *Frangible sign supports, part 1: recommended procedures for design, testing, installation and maintenance; part 2: state of the art review*. Sydney, NSW, Australia: Austroads.
- Muthubandara, N., Eveleigh, M., Kung, L., & Spathonis, J. (2017/in-press). *A crash testing evaluation of road signs to mitigate vehicle windscreen spearing risk*. Paper presented at Australasian Road Safety Conference, Perth, WA, Australia.
- New South Wales Roads and Traffic Authority. (2010). *Installation and maintenance of signs*. NSW RTA Internal working document.
- New Zealand Transport Agency. (2008). *Traffic signs performance based specification TNZ P/24*. New Zealand.
- Queensland Department of Transport and Main Roads. (2001). *Design guide for roadside signs*. Brisbane, Queensland, Australia.
- Road Safety Manufacturers' Association. (2008). *RSMA compliance standard for traffic signs*. New Zealand.
- Ross, H. E., Perera, H. S., Sicking, D. L., & Bligh, R. P. (1989). *Roadside safety design for small vehicles*. Washington, DC, USA: Transportation Research Board.
- Savin, S. J. (2003). *Passive safety tests on steel circular hollow section sign posts*. Crowthorne, Berkshire, United Kingdom: Transportation Research Laboratory.
- South Australia DPTI. (2016). *Specification Part R49 Installation of signs*. Adelaide, SA, Australia.
- Standards Australia. (2009). *AS 1742.2 Manual of uniform traffic control devices: Traffic control devices for general use*. Strathfield, New South Wales, Australia.
- Standards Australia. (2016). *AS/NZS 1163: Cold-formed structural steel hollow sections*. Strathfield, New South Wales, Australia; Wellington, New Zealand.
- Standards Australia. (2017). *AS/NZS 3845.2 Road safety barrier systems and devices - road safety devices*. Strathfield, New South Wales, Australia; Wellington, New Zealand.
- VicRoads. (2015). *Supplement to AS 1742.2:2009 Manual of uniform traffic control devices Part 15: Traffic control devices for general use*. Melbourne, Victoria, Australia.