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Research Report No R895

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Abstract:

The report describes the findings from various site measurements of geometric imperfections on support scaffold systems, also known as falsework in industry. The measurements consist of out-of-straightness of the standards (uprights), out-of-plumb of the frame and loading eccentricity between the timber bearer and the U-head. A special-made tool instrumented with a dial gauge was used to measure the out-of-straightness of standards at the mid-height of each lift. A theodolite was employed to measure the angle difference between top and bottom of the frame in order to compute storey out-of-plumb, and a vernier calliper was used to measure the loading eccentricity at the top. The measurements were taken from different support scaffold construction sites before the pouring of concrete, representing actual initial imperfections and loading eccentricity encountered in practice.

Keywords:
Geometric imperfections, Out-of-straightness, Out-of-plumb, Loading eccentricity, Support scaffold systems, Falsework

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1. Introduction

Support scaffold systems are used to temporarily support heavy loads such as weight of fresh concrete, formwork, rebar, equipment and workers. In construction, the components of scaffold systems are used repeatedly to save cost; therefore, they usually show signs of wear and out-of-straightness of members. In addition, scaffold systems generally show some degree of out-of plumb of the frame as a result of uneven ground surface or imperfection in materials. Due to heavy loads and geometric imperfections of the systems, the strength and behaviour of support scaffolds are susceptible to adverse 2nd order member P-δ and frame P-Δ effects.

Significant research has been made in incorporating geometric imperfections in the structural analysis model of steel frame during the past [1-3]. Two main types of geometric imperfections consisting of initial out-of-plumb (sway) and initial member out-of-straightness (crookedness) are particularly important in modelling. A common approach of incorporating geometric imperfections is to scale one or more critical elastic buckling modes and add the scaled displacements to the perfect geometry. However, many issues arise with this method, for instance, how many buckling modes should be included and what scaling factors should be applied. One option is to use the maximum allowable imperfection values from available structural codes; for example, the Australian steel design standard [4] specifies a maximum out-of-straightness of L/1000, where L is the member length. Nonetheless, this method often produces conservative predictions of the strength of the systems. An alternative approach is to apply notional horizontal forces, but some doubts remain about the magnitude of the forces and at which positions they should be applied on the frame.

In order to resolve the issue of imperfections in scaffold systems, actual data of geometric imperfections is needed. At present, no available data is published for geometric imperfections of scaffold systems. This research presents the methods and results in the procurement of geometric imperfection data including measurements of the loading eccentricity between the timber bearer and the U-head for Cuplok scaffold systems.

The Cuplok scaffold systems (Figure 1) in this study consists of standards, attached with Cuplok joints, made from cold-formed circular steel tube grade 450 MPa with nominal outside diameter of 48.3 mm and thickness of 4 mm. The grade 350 MPa ledgers made of steel tube with nominal outside diameter of 48.3 mm and thickness of 3.2 mm attached with end blades are connected to the standards via Cuplok joints. The telescopic braces with hook ends were made of 48.3 mm x 4.0 mm outer tube and 38.2 mm x 3.2 mm inner tube with nominal yield stress of 400 MPa. The adjustable jacks with 600 mm maximum extension capability were made of 36 mm diameter threaded steel rod in grade 430 MPa and the base plates were 180 mm x 180 mm x 10 mm in dimensions with nominal yield stress of 250 MPa. The U-heads attached to the jacks have clear width of 210 mm.

The data of geometric imperfections and load eccentricity was collected from four different construction sites around Sydney area by the use of custom-made tools, measuring equipment and theodolite. In order to obtain a wide representative range of imperfection and load eccentricity values for support scaffold systems, each construction site was for different functions such as train station platform, residential building, parking structure and office building. Moreover, different supporting ground conditions such as concrete slab and compacted ground were observed from one location to another, representing a broad range of out-of-plumb values. At the sites, Cuplok scaffold systems were comprised of 1 to 3 lifts with the lift heights of 1 m and 1.5 m; also, typical jack extensions were varied between 200 mm and 400 mm. Positions of the spigot joints were observed to be random and usually in 2nd or 3rd lift.

Figure 1: Cuplok scaffold systems

2. Methods of Procurement

A special-made device instrumented with a dial gauge was used to measure the out-of-straightness (crookedness) of the standards (uprights) at the mid-height of each lift in two perpendicular directions aligned with the ledgers and referred to as the N-S and E-W directions. Figure 2 shows schematics of the device in two different lengths that fit into 1 m and 1.5 m lift heights of the scaffold systems for out-of-straightness measurement. The dial gauge attached to the device was calibrated with a perfectly flat surface so that it read directly the imperfection value once aligned with the standard. Figure 3(a) shows the actual devices used to measure the out-of straightness at mid-height of the standard in the lift and Figure 3(b) exemplifies the measurement of the out-of-straightness of a 1 m lift standard on one of the sites.

A theodolite was set up to measure the angle difference between top and bottom of the frame in order to compute storey out-of-plumb (Figure 4). The horizontal distance between the standard (upright) and the theodolite was also measured together with the angle difference so that a simple trigonometric calculation could be carried out to calculate the storey out-of-plumb. Measurements were made for both the N-S and E-W axes of the construction plans.

A vernier calliper was used to measure the loading eccentricity at the top between the centrelines of the timber bearer and the U-head. All measurements were taken before the pouring of concrete on to the formwork, representing actual initial geometric imperfections and loading eccentricity encountered in practice.

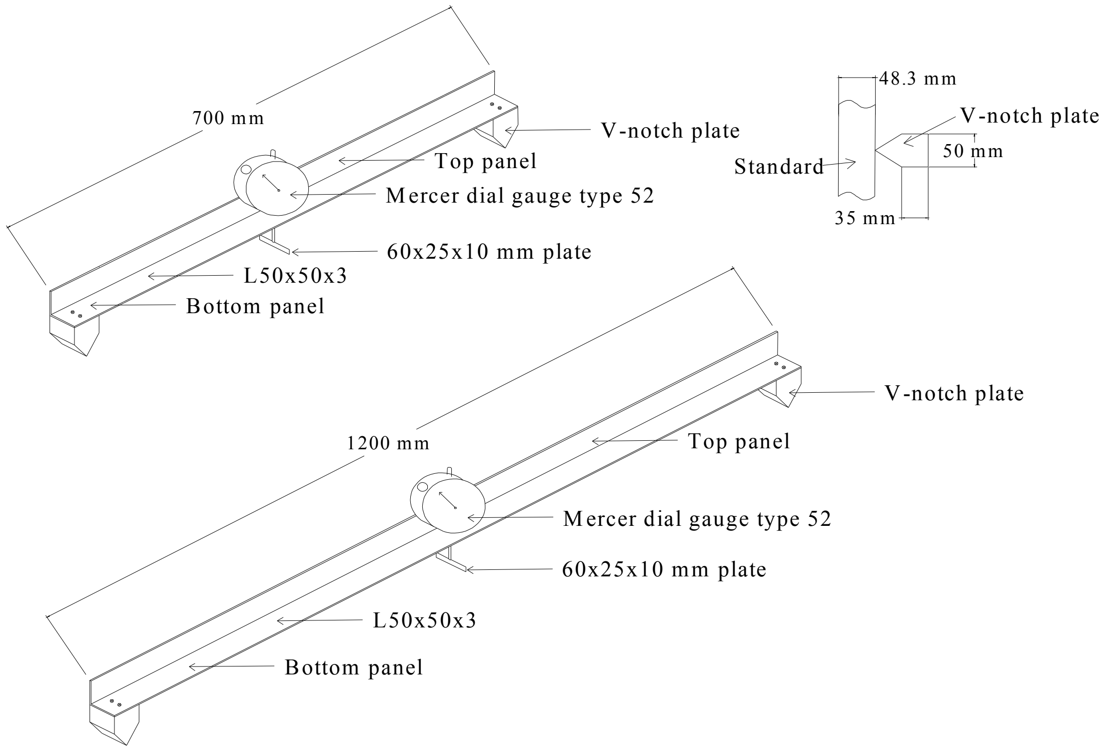

Figure 2: Schematic of device used to measure out-of-straightness

(a)

(b)

Figure 3: (a) Device used to measure out-of-straightness (b) Actual measurement

Figure 4: Theodolite employed for storey out-of-plumb measurement

3. Survey Results of Geometric Imperfections and Loading Eccentricity

A total of 302 on-site measurements of out-of-straightness of the standard were taken and 80 measurements of storey out-of-plumb were acquired. In addition, 74 measurements of loading eccentricity were obtained from various construction sites. From data observation, it was found that there was no correlation between the out-of-straightness of the standards and the storey out-of-plumb; moreover, the directions (axes) of these geometric imperfections were random. The directions of the loading eccentricity were shown to be random and occurred on either side perpendicular to the bearer. The results of out-of-straightness of the standards were normalised with the lift height and the results of storey out-of-plumb were normalised with the storey height of the scaffold systems measuring from base plate up to the U-head. Figures 5-7 show the histograms of normalised out-of-straightness of the standards (δ/L_h where δ is the deflection at mid-height of the lift and L_h is the lift height), normalised storey out-of-plumb (Δ/H where Δ is the sway and H is the height of the scaffold systems) and loading eccentricity, respectively. A complete data can be found in Appendix A.

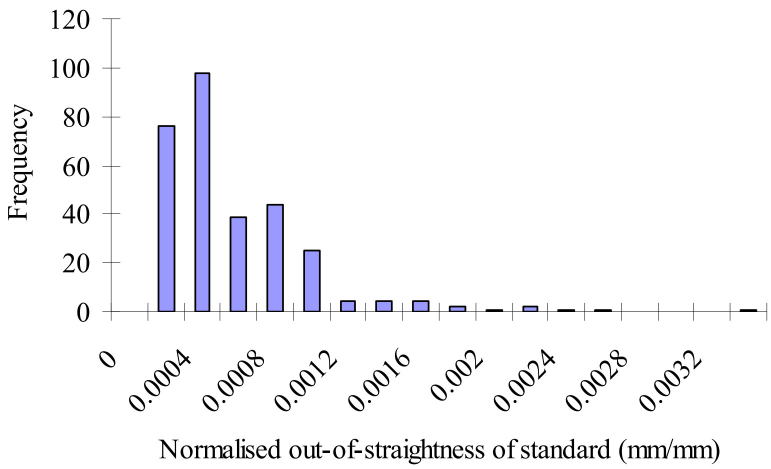

Figure 5: Histogram of normalised out-of-straightness of the standards (δ/L_h)

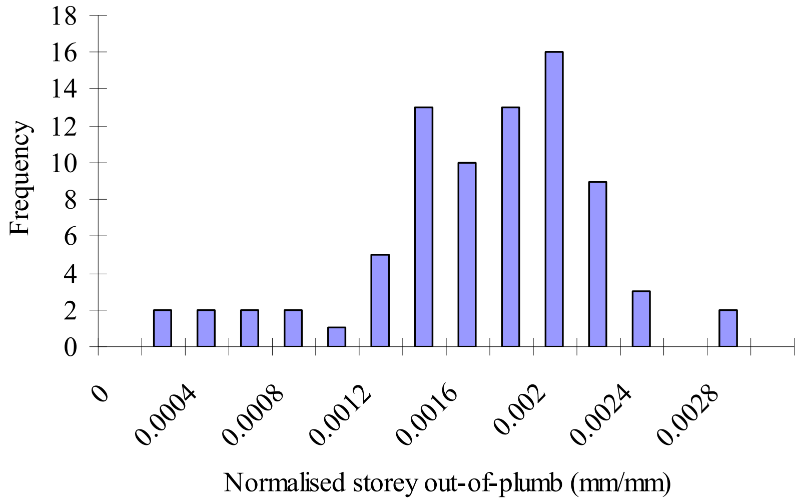

Figure 6: Histogram of normalised storey out-of-plumb (Δ/H)

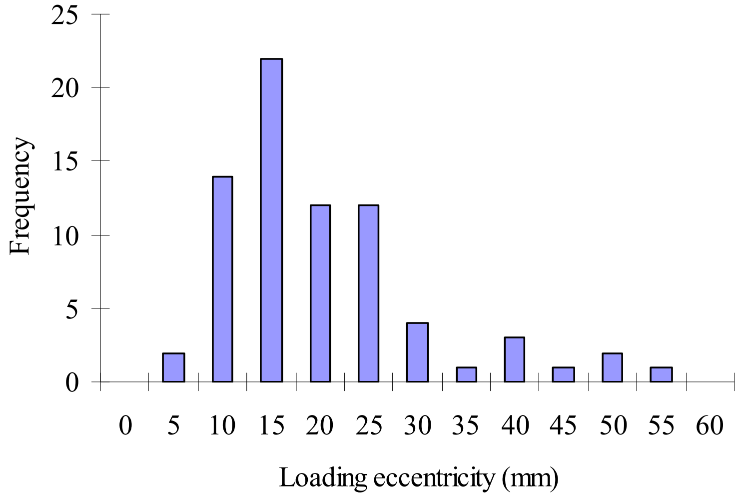

Figure 7: Histogram of loading eccentricity

The mean normalised out-of-straightness of the standards including standards with and without spigot joints is 0.00048 (L_h/2080) with standard deviation of 0.00042; however, it is computed that the mean normalised out-of-straightness of the standards with spigot joints is 0.0013 (L_h/770) with standard deviation of 0.0008 and the mean normalised out-of-straightness of the standards without spigot joints is 0.0004 (L_h/2500) with standard deviation of 0.0003. The mean normalised storey out-of-plumb is 0.0016 (H/625) with standard deviation of 0.0005 whereas the mean loading eccentricity is 18.09 mm with standard deviation of 10.67 mm.

4. Discussion

The geometric imperfection and loading eccentricity data was obtained from Cuplok scaffold systems; therefore, other support formwork systems may present a different range of values of geometric imperfections and loading eccentricity when compared to this data. Nevertheless, this data gives a general expectation of the level of geometric imperfections and loading eccentricity in other support scaffold systems. It is possible that weaker systems, such as wedge-type scaffolds, might present higher values of geometric imperfections since members of such systems are usually more flexible as they tend to have smaller crosssections, and upright-to-beam connections are less stiff. The level of geometric imperfections in scaffold systems is expected to depend primarily on section properties, material properties, methods of construction and numbers of repeated uses. For loading eccentricity, it is obvious that the magnitude depends on the clear width of the U-head that the bearer sits on; besides, in good construction practice the U-head is twisted against the timber bearer to minimise the amount of loading eccentricity.

The mean of the normalised out-of-straightness of the standards without spigot joints shows a somewhat smaller value than the maximum permissible out-of-straightness of L/1000 where L is the member length in the Australian design standard for steel structures [4]; however, the mean of the normalised out-of-straightness of the standards with spigot joints is larger than the maximum permissible out-of-straightness value from the code, suggesting that it is not conservative to adopt the code value for modelling scaffold lifts with spigot joints. The mean of the normalised storey out-of-plumb of H/625 is within the maximum allowable out-of-plumb of H/400 where H is the height of the scaffold systems in the Australian standard of formwork for concrete [5]. For loading eccentricity, the Australian code [5] limits the eccentricity at 40 mm or 25% of the bearer width, whichever is less (18.75 mm for the systems investigated herein). According to the data obtained, the mean of the loading eccentricity of 18.09 mm is still within this limit; nonetheless, adopting the code recommended loading eccentricity for modelling and analysis may not produce conservative results since higher magnitude of loading eccentricity might occur.

Ultimately, these uncertainties must be studied by statistical methods to find appropriate distributions so that probabilistic assessment of the strength of the support scaffold systems can be carried out. Table 1 shows fitted statistical functions for the normalised out-of-straightness of the standards (δ/L_h), the normalised storey out-of-plumb (Δ/H) and the loading eccentricity of the support scaffold systems. The fitted probability distributions are shown graphically in Figure 8-11.

Table 1: Fitted probability distributions for the normalised out-of-straightness, the normalised out-of-plumb and the loading eccentricity of the support scaffold systems

Random variable	Probability distribution	Mean	Standard deviation
Normalised out-of-straightness of the standards without spigot joints (δ/L_h)	Lognormal	0.0004	0.0003
Normalised out-of-straightness of the standards with spigot joints (δ/L_h)	Lognormal	0.0013	0.0008
Normalised storey out-of-plumb (Δ/H)	Normal	0.0016	0.0005
Loading eccentricity	Lognormal	18.09 mm	10.67 mm

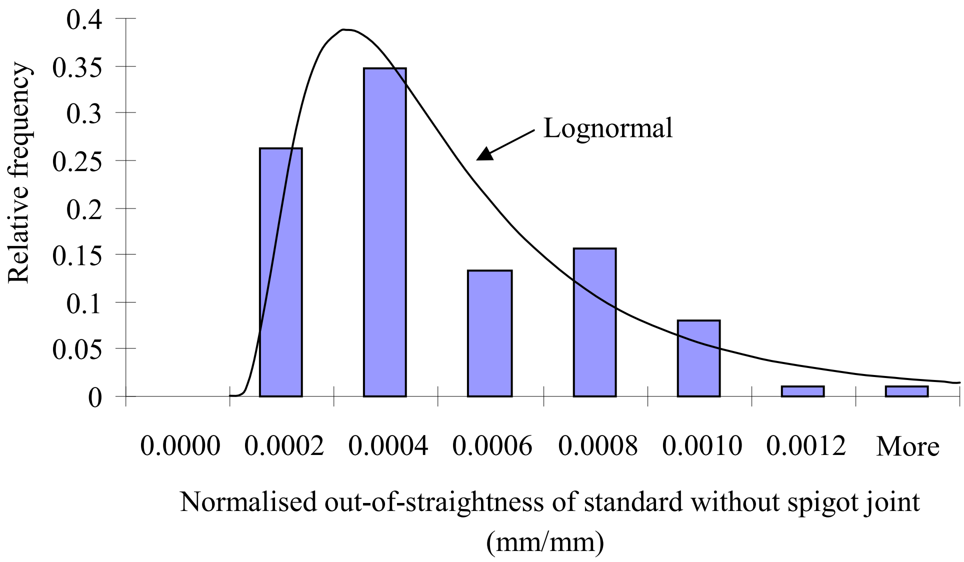

Figure 8: Fitted lognormal distribution of normalised out-of-straightness of standards without spigot joints

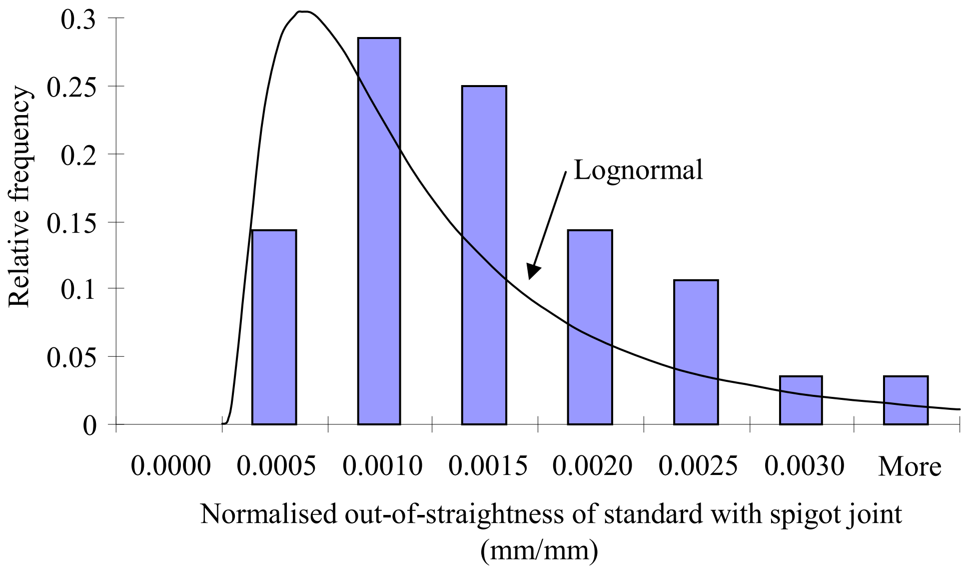

Figure 9: Fitted lognormal distribution of normalised out-of-straightness of standards with spigot joints

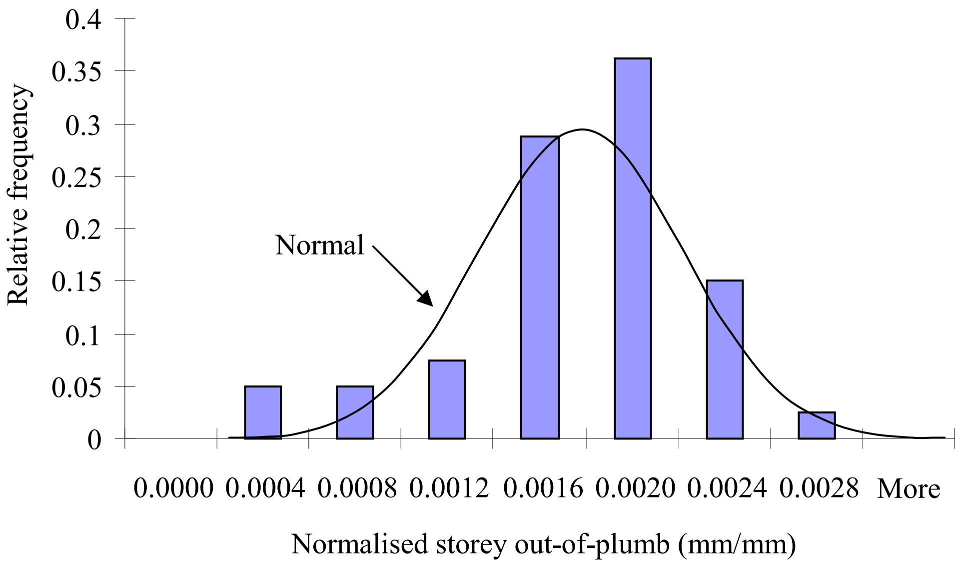

Figure 10: Fitted normal distribution of normalised storey out-of-plumb

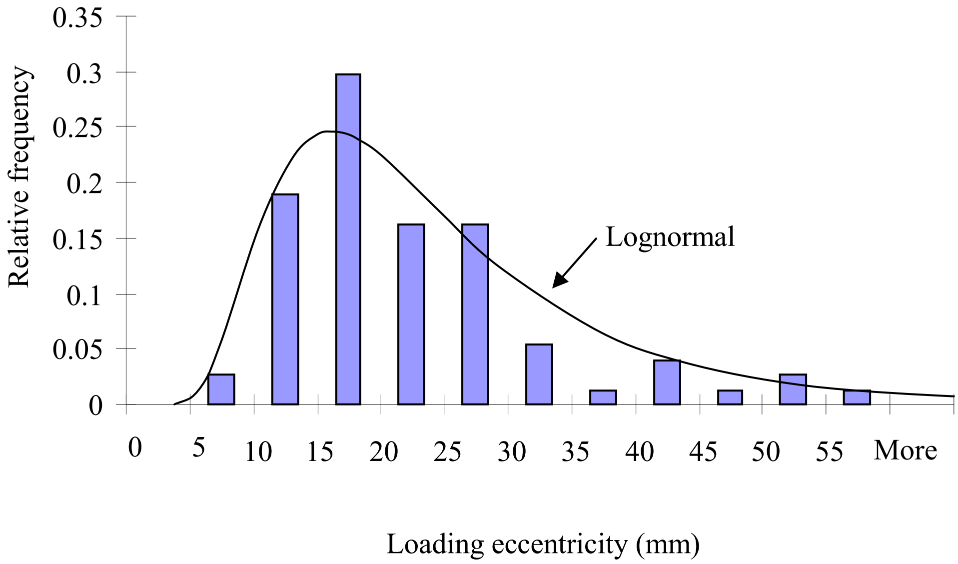

Figure 11: Fitted lognormal distribution of loading eccentricity

5. Conclusions

In this research, measurements of geometric imperfections and loading eccentricity of Cuplok support scaffold systems have been obtained from various construction sites in the Sydney area, and the results are presented as histograms and fitted statistical functions. The statistics of the data are presented and compared to the values from the Australian standards [4, 5]. By code comparison to the mean values, it is shown that the actual out-of-straightness of standards with spigot joints is over the limit imposed by the code [4]; in addition, the magnitude of the loading eccentricity may be higher than the expected loading eccentricity from the code [5]. Consequently, structural modelling based on the codes might lead to less conservative or inadequate design of support scaffold systems. Nevertheless, the mean of the storey out-of-plumb is shown to be well within the limit imposed by the code [5]. The probability distributions for geometric imperfections and loading eccentricity are presented for further use in probabilistic assessment of the strength of the support scaffold systems.

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[5] Standard Australia. AS 3610: Formwork for concrete. 1995.

Appendix A

Table A1: Data for out-of-straightness of the standards
(TS = Top lift standard, BS = Bottom lift standard, A = Train station platform, B = Parking structure, C = Residential building and D = Office building)

Site	Grid location	Member	Lift height (m)	Out-of-straightness		Normalised out-of-straightness		Note
				X-Axis (mm)	Y-Axis (mm)	X-Axis (mm/mm)	Y-Axis (mm/mm)	
A	19x15	TS	1	3.36	-1.2	0.00336	0.00120	spigot
A	19x15	BS	1	0.9	0.35	0.00090	0.00035	
A	20x14	BS	1	-0.86	0.86	0.00086	0.00086	
A	20x14	TS	1	0.85	-0.51	0.00085	0.00051	
A	23x15	BS	1	0.14	-0.21	0.00014	0.00021	
A	23x15	TS	1	1.61	0.11	0.00161	0.00011	spigot
A	24x14	TS	1	1.81	2.6	0.00181	0.00260	spigot
A	24x14	BS	1	0.16	-0.23	0.00016	0.00023	
A	28x17	BS	1	0.38	0.25	0.00038	0.00025	
A	28x17	TS	1	0.35	-0.28	0.00035	0.00028	
A	27x16	BS	1	-0.18	-0.95	0.00018	0.00095	
A	27x16	TS	1	0.84	0.43	0.00084	0.00043	
A	29x17	BS	1	-0.26	0.22	0.00026	0.00022	
A	29x17	TS	1	-2.13	-1.21	0.00213	0.00121	spigot
A	30x17	BS	1	0.39	0.42	0.00039	0.00042	
A	30x17	TS	1	-0.4	-1.6	0.00040	0.00160	
A	19x10	BS	1	-0.8	-0.12	0.00080	0.00012	
A	19x10	TS	1	0.26	0.72	0.00026	0.00072	
A	19x11	BS	1	0.55	-0.9	0.00055	0.00090	
A	19x11	TS	1	1.2	-0.22	0.00120	0.00022	spigot
A	20x10	BS	1	-0.14	0.12	0.00014	0.00012	
A	20x10	TS	1	0.56	-0.2	0.00056	0.00020	
A	30x11	BS	1	0.12	0.21	0.00012	0.00021	
A	30x11	TS	1	0.42	0.69	0.00042	0.00069	
A	29x11	BS	1	0.13	-0.14	0.00013	0.00014	
A	29x11	TS	1	0.72	-0.35	0.00072	0.00035	
A	1x1	BS	1	0.31	-0.25	0.00031	0.00025	
A	1x2	BS	1	-0.41	0.12	0.00041	0.00012	
A	2x1	BS	1	0.45	0.51	0.00045	0.00051	
A	2x2	BS	1	0.22	-0.15	0.00022	0.00015	
A	1x1	TS	1	-0.3	0.12	0.00030	0.00012	
A	1x2	TS	1	-0.43	0.41	0.00043	0.00041	
A	2x1	TS	1	-0.11	0.52	0.00011	0.00052	
A	2x2	TS	1	0.24	-0.48	0.00024	0.00048	
A	3x1	BS	1	0.23	0.2	0.00023	0.00020	
A	4x1	BS	1	-0.45	0.1	0.00045	0.00010	
A	3x2	BS	1	0.1	-0.34	0.00010	0.00034	
A	4x2	BS	1	0.25	0.35	0.00025	0.00035	
A	3x1	TS	1	0.32	0.42	0.00032	0.00042	
A	4x1	TS	1	0.25	-0.41	0.00025	0.00041	

Site	Grid location	Member	Lift height (m)	Out-of-straightness X-Axis (mm)	Out-of-straightness Y-Axis (mm)	Normalised out-of-straightness X-Axis (mm/mm)	Normalised out-of-straightness Y-Axis (mm/mm)	Note
A	3x2	TS	1	0.53	-0.1	0.00053	0.00010	
A	4x2	TS	1	0.31	0.32	0.00031	0.00032	
A	5x1	BS	1	0.46	0.1	0.00046	0.00010	
A	5x2	BS	1	0.56	0.07	0.00056	0.00007	
A	6x1	BS	1	-0.7	-0.05	0.00070	0.00005	
A	6x2	BS	1	-0.2	0.12	0.00020	0.00012	
A	5x1	TS	1	0.1	-0.23	0.00010	0.00023	
A	5x2	TS	1	0.08	-0.25	0.00008	0.00025	
A	6x1	TS	1	0.12	0.36	0.00012	0.00036	
A	6x2	TS	1	0.09	0.07	0.00009	0.00007	
B	1x1	BS	1	0.26	-0.2	0.00026	0.00020	
B	1x2	BS	1	0.2	-0.19	0.00020	0.00019	
B	1x3	BS	1	0.25	-0.18	0.00025	0.00018	
B	1x4	BS	1	0.19	0.2	0.00019	0.00020	
B	1x5	BS	1	0.12	0.08	0.00012	0.00008	
B	1x6	BS	1	-0.38	0.2	0.00038	0.00020	
B	1x7	BS	1	-0.15	0.21	0.00015	0.00021	
B	1x8	BS	1	0.2	0.1	0.00020	0.00010	
B	1x9	BS	1	0.1	0.18	0.00010	0.00018	
B	1x10	BS	1	0.32	-0.12	0.00032	0.00012	
B	1x11	BS	1	0.6	0.14	0.00060	0.00014	
B	1x12	BS	1	0.25	0.23	0.00025	0.00023	
B	1x13	BS	1	0.32	-0.26	0.00032	0.00026	
B	1x14	BS	1	0.5	-0.4	0.00050	0.00040	
B	1x15	BS	1	-0.42	0.35	0.00042	0.00035	
B	1x16	BS	1	0.32	-0.25	0.00032	0.00025	
B	1x17	BS	1	0.23	-0.34	0.00023	0.00034	
B	1x18	BS	1	-0.45	0.23	0.00045	0.00023	
B	1x19	BS	1	0.3	-0.38	0.00030	0.00038	
B	1x20	BS	1	0.39	-0.25	0.00039	0.00025	
B	1x1	TS	1	0.15	-0.21	0.00015	0.00021	
B	1x2	TS	1	0.18	0.23	0.00018	0.00023	
B	1x3	TS	1	0.25	-0.32	0.00025	0.00032	
B	1x4	TS	1	-0.32	0.24	0.00032	0.00024	
B	1x5	TS	1	-0.14	0.19	0.00014	0.00019	
B	1x6	TS	1	0.25	0.18	0.00025	0.00018	
B	1x7	TS	1	0.5	-0.48	0.00050	0.00048	
B	1x8	TS	1	0.15	-0.23	0.00015	0.00023	
B	1x9	TS	1	-0.24	0.34	0.00024	0.00034	
B	1x10	TS	1	0.32	0.24	0.00032	0.00024	
B	1x11	TS	1	0.51	-0.39	0.00051	0.00039	
B	1x12	TS	1	0.18	0.28	0.00018	0.00028	
B	1x13	TS	1	0.26	-0.25	0.00026	0.00025	
B	1x14	TS	1	0.38	-0.41	0.00038	0.00041	
B	1x15	TS	1	0.25	0.15	0.00025	0.00015	
B	1x16	TS	1	1.0	1.3	0.00100	0.00130	spigot
B	1x17	TS	1	0.26	0.18	0.00026	0.00018	
B	1x18	TS	1	-0.12	0.19	0.00012	0.00019	

Site	Grid location	Member	Lift height (m)	Out-of-straightness X-Axis (mm)	Out-of-straightness Y-Axis (mm)	Normalised out-of-straightness X-Axis (mm/mm)	Normalised out-of-straightness Y-Axis (mm/mm)	Note
B	1x19	TS	1	0.26	-0.15	0.00026	0.00015	
B	1x20	TS	1	0.18	0.24	0.00018	0.00024	
C	2x1	BS	1.5	-1.1	0.6	0.00073	0.00040	
C	2x2	BS	1.5	-1.3	0.5	0.00087	0.00033	
C	2x3	BS	1.5	1.6	-0.5	0.00107	0.00033	
C	2x4	BS	1.5	-0.9	1.1	0.00060	0.00073	
C	2x5	BS	1.5	1.1	-1	0.00073	0.00067	
C	2x6	BS	1.5	-0.95	0.1	0.00063	0.00007	
C	2x7	BS	1.5	0.35	-0.2	0.00023	0.00013	
C	2x8	BS	1.5	1.12	-0.52	0.00075	0.00035	
C	2x9	BS	1.5	0.2	-0.24	0.00013	0.00016	
C	2x10	BS	1.5	0.98	-0.75	0.00065	0.00050	
C	2x11	BS	1.5	-1.13	-1.3	0.00075	0.00087	
C	2x12	BS	1.5	-1.23	0.51	0.00082	0.00034	
C	2x13	BS	1.5	0.71	-0.43	0.00047	0.00029	
C	2x14	BS	1.5	-1.12	0.42	0.00075	0.00028	
C	2x1	TS	1.5	3.12	3.5	0.00208	0.00233	spigot
C	2x2	TS	1.5	-1.21	1.35	0.00081	0.00090	
C	2x3	TS	1.5	2.1	-2.15	0.00140	0.00143	spigot
C	2x4	TS	1.5	-1.54	-1.12	0.00103	0.00075	
C	2x5	TS	1.5	1.24	1.1	0.00083	0.00073	
C	2x6	TS	1.5	1.1	-2.5	0.00073	0.00167	spigot
C	2x7	TS	1.5	2.4	-1.1	0.00160	0.00073	spigot
C	2x8	TS	1.5	1.55	-1.45	0.00103	0.00097	
C	2x9	TS	1.5	0.54	-1.49	0.00036	0.00099	
C	2x10	TS	1.5	0.56	0.12	0.00037	0.00008	
C	2x11	TS	1.5	0.95	-0.85	0.00063	0.00057	
C	2x12	TS	1.5	0.9	-0.25	0.00060	0.00017	
C	2x13	TS	1.5	1.4	0.14	0.00093	0.00009	
C	2x14	TS	1.5	0.92	-1.3	0.00061	0.00087	
C	3x1	TS	1.5	0.43	-0.32	0.00029	0.00021	
C	3x2	TS	1.5	1.25	0.5	0.00083	0.00033	spigot
C	3x3	TS	1.5	-0.27	0.5	0.00018	0.00033	
C	3x4	TS	1.5	1.1	1.12	0.00073	0.00075	
C	3x5	TS	1.5	-0.32	0.95	0.00021	0.00063	
C	3x6	TS	1.5	0.15	0.58	0.00010	0.00039	
C	3x7	TS	1.5	1.12	-0.15	0.00075	0.00010	spigot
C	3x8	TS	1.5	1.4	0.9	0.00093	0.00060	spigot
C	3x9	TS	1.5	-0.7	0.3	0.00047	0.00020	
D	1x1	BS	1.5	0.1	1.42	0.00007	0.00095	
D	1x2	BS	1.5	-0.3	0.15	0.00020	0.00010	
D	2x1	BS	1.5	0.9	-1.12	0.00060	0.00075	
D	2x2	BS	1.5	1	1.1	0.00067	0.00073	
D	1x1	TS	1	-0.35	0.4	0.00035	0.00040	
D	1x2	TS	1	0.45	0.63	0.00045	0.00063	
D	2x1	TS	1	0.51	0.62	0.00051	0.00062	

Site	Grid location	Member	Lift height (m)	Out-of-straightness		Normalised out-of-straightness		Note
				X-Axis (mm)	Y-Axis (mm)	X-Axis (mm/mm)	Y-Axis (mm/mm)	
D	2x2	TS	1	-0.23	-0.1	0.00023	0.00010	
D	3x1	BS	1.5	2.14	-1.12	0.00143	0.00075	spigot
D	4x1	BS	1.5	1.13	-0.95	0.00075	0.00063	
D	3x2	BS	1.5	-1.23	0.56	0.00082	0.00037	
D	4x2	BS	1.5	1.93	-1.02	0.00129	0.00068	
D	3x1	TS	1	-0.94	0.62	0.00094	0.00062	
D	4x1	TS	1	0.51	-0.31	0.00051	0.00031	
D	3x2	TS	1	0.43	0.78	0.00043	0.00078	
D	4x2	TS	1	0.96	-0.42	0.00096	0.00042	
D	5x1	BS	1.5	-1.41	0.32	0.00094	0.00021	
D	5x2	BS	1.5	0.98	-1.93	0.00065	0.00129	
D	6x1	BS	1.5	0.86	1.12	0.00057	0.00075	
D	6x2	BS	1.5	1.1	-1.45	0.00073	0.00097	
D	5x1	TS	1	0.44	0.61	0.00044	0.00061	
D	5x2	TS	1	0.36	-0.79	0.00036	0.00079	
D	6x1	TS	1	0.78	0.1	0.00078	0.00010	
D	6x2	TS	1	0.21	0.14	0.00021	0.00014	

Table A2: Data for storey out-of-plumb
(C = Residential building and D = Office building)

Site	Grid location / Direction	Bottom horizontal angle (degree)	Top horizontal angle (degree)	X-axis sway (mm)	Y-axis sway (mm)	Length from origin (m)	Height (m)	Normalised out-of-plumb (mm/mm)
C	1x1 (North)	122.167	122.233	Nil	-3.72	3.20	3.00	0.00124
C	2x1 (North)	107.358	107.342	Nil	0.91	3.12	3.00	0.00030
C	3x1 (North)	280.250	279.883	Nil	8.01	1.25	3.00	0.00267
C	4x1 (North)	307.083	307.250	Nil	-5.98	2.05	3.00	0.00199
C	5x1 (North)	314.442	314.600	Nil	-5.93	2.15	3.00	0.00198
C	1x2 (North)	350.803	350.391	Nil	7.91	1.10	3.00	0.00264
C	2x2 (North)	337.250	337.520	Nil	-6.36	1.35	3.00	0.00212
C	3x2 (North)	412.321	412.100	Nil	5.40	1.40	3.00	0.00180
C	4x2 (North)	71.317	71.512	Nil	-5.79	1.70	3.00	0.00193
C	5x2 (North)	134.583	134.700	Nil	-5.11	2.50	3.00	0.00170
C	1x3 (North)	111.233	111.317	Nil	-4.40	3.00	3.00	0.00147

Site	Grid location / Direction	Bottom horizontal angle (degree)	Top horizontal angle (degree)	X-axis sway (mm)	Y-axis sway (mm)	Length from origin (m)	Height (m)	Normalised out-of-plumb (mm/mm)
C	2x3 (North)	140.633	140.533	Nil	4.36	2.50	3.00	0.00145
C	3x3 (North)	89.700	89.817	Nil	-5.21	2.55	3.00	0.00174
C	4x3 (North)	120.750	120.867	Nil	-3.98	1.95	3.00	0.00133
C	5x3 (North)	114.250	114.367	Nil	-5.00	2.45	3.00	0.00167
C	1x4 (North)	230.725	230.825	Nil	-4.63	2.65	3.00	0.00154
C	2x4 (North)	331.992	331.858	Nil	4.98	2.13	3.00	0.00166
C	3x4 (North)	320.208	320.308	Nil	-3.75	2.15	3.00	0.00125
C	4x4 (North)	340.442	340.525	Nil	-3.16	2.18	3.00	0.00105
C	5x4 (North)	315.775	315.692	Nil	3.26	2.25	3.00	0.00109
C	1x1 (East)	11.542	11.575	-1.41	Nil	2.45	3.00	0.00047
C	2x1 (East)	21.517	21.417	3.89	Nil	2.23	3.00	0.00130
C	3x1 (East)	50.733	50.833	-4.45	Nil	2.55	3.00	0.00148
C	4x1 (East)	65.416	65.483	-3.25	Nil	2.78	3.00	0.00108
C	5x1 (East)	32.517	32.583	-4.09	Nil	3.55	3.00	0.00136
C	1x2 (East)	154.203	154.192	0.47	Nil	2.43	3.00	0.00016
C	2x2 (East)	170.358	170.408	-2.33	Nil	2.67	3.00	0.00078
C	3x2 (East)	175.517	175.633	-5.85	Nil	2.89	3.00	0.00195
C	4x2 (East)	146.350	146.200	5.68	Nil	2.17	3.00	0.00189
C	5x2 (East)	151.517	151.417	4.10	Nil	2.35	3.00	0.00137
C	1x3 (East)	95.717	95.850	-5.22	Nil	2.25	3.00	0.00174
C	2x3 (East)	83.683	83.817	-5.03	Nil	2.15	3.00	0.00168
C	3x3 (East)	87.850	87.983	-5.08	Nil	2.19	3.00	0.00169
C	4x3 (East)	101.467	101.433	1.16	Nil	1.95	3.00	0.00039
C	5x3 (East)	79.192	79.203	-0.45	Nil	2.35	3.00	0.00015

Site	Grid location / Direction	Bottom horizontal angle (degree)	Top horizontal angle (degree)	X-axis sway (mm)	Y-axis sway (mm)	Length from origin (m)	Height (m)	Normalised out-of-plumb (mm/mm)
C	1x4 (East)	65.208	65.308	-4.15	Nil	2.38	3.00	0.00138
C	2x4 (East)	62.458	62.392	2.48	Nil	2.15	3.00	0.00083
C	3x4 (East)	87.258	87.287	-1.40	Nil	2.76	3.00	0.00047
C	4x4 (East)	97.367	97.517	-6.94	Nil	2.65	3.00	0.00231
C	5x4 (East)	109.850	109.983	-5.69	Nil	2.45	3.00	0.00190
D	1x1 (North)	102.200	102.417	Nil	-9.47	2.50	5.00	0.00189
D	2x1 (North)	115.767	115.583	Nil	8.74	2.72	5.00	0.00175
D	3x1 (North)	108.700	108.850	Nil	-7.85	3.00	5.00	0.00157
D	4x1 (North)	106.192	106.350	Nil	-9.65	3.50	5.00	0.00193
D	5x1 (North)	110.321	110.208	Nil	6.61	3.35	5.00	0.00132
D	1x2 (North)	24.083	23.933	Nil	9.32	3.56	5.00	0.00186
D	2x2 (North)	34.367	34.520	Nil	-10.33	3.87	5.00	0.00207
D	3x2 (North)	38.200	38.350	Nil	-9.56	3.65	5.00	0.00191
D	4x2 (North)	21.600	21.733	Nil	-7.52	3.24	5.00	0.00150
D	5x2 (North)	36.650	36.517	Nil	8.70	3.75	5.00	0.00174
D	1x3 (North)	230.183	230.325	Nil	-8.55	3.45	5.00	0.00171
D	2x3 (North)	245.633	245.533	Nil	5.45	3.12	5.00	0.00109
D	3x3 (North)	254.716	254.842	Nil	-8.58	3.90	5.00	0.00172
D	4x3 (North)	223.350	223.200	Nil	9.53	3.64	5.00	0.00191
D	5x3 (North)	210.433	210.558	Nil	-6.81	3.12	5.00	0.00136
D	1x4 (North)	124.808	124.692	Nil	6.17	3.05	5.00	0.00123
D	2x4 (North)	146.100	146.242	Nil	-9.42	3.80	5.00	0.00188
D	3x4 (North)	152.542	152.442	Nil	6.37	3.65	5.00	0.00127
D	4x4 (North)	115.708	115.842	Nil	-8.07	3.45	5.00	0.00161

Site	Grid location / Direction	Bottom horizontal angle (degree)	Top horizontal angle (degree)	X-axis sway (mm)	Y-axis sway (mm)	Length from origin (m)	Height (m)	Normalised out-of-plumb (mm/mm)
D	5x4 (North)	170.458	170.517	Nil	-3.45	3.35	5.00	0.00069
D	1x1 (East)	310.683	310.533	9.61	Nil	3.67	5.00	0.00192
D	2x1 (East)	305.200	305.317	-7.94	Nil	3.89	5.00	0.00159
D	3x1 (East)	340.100	340.258	-11.03	Nil	4.00	5.00	0.00221
D	4x1 (East)	345.767	345.933	-10.86	Nil	3.75	5.00	0.00217
D	5x1 (East)	358.675	358.542	7.43	Nil	3.20	5.00	0.00149
D	1x2 (East)	220.992	220.875	7.56	Nil	3.70	5.00	0.00151
D	2x2 (East)	234.242	234.375	-8.05	Nil	3.47	5.00	0.00161
D	3x2 (East)	245.208	245.375	-10.38	Nil	3.56	5.00	0.00208
D	4x2 (East)	257.558	257.708	-10.13	Nil	3.87	5.00	0.00203
D	5x2 (East)	238.692	238.583	6.09	Nil	3.20	5.00	0.00122
D	1x3 (East)	32.300	32.417	-7.84	Nil	3.84	5.00	0.00157
D	2x3 (East)	45.225	45.067	10.37	Nil	3.76	5.00	0.00207
D	3x3 (East)	51.467	51.625	-10.07	Nil	3.65	5.00	0.00201
D	4x3 (East)	60.383	60.275	6.50	Nil	3.45	5.00	0.00130
D	5x3 (East)	23.450	23.283	11.02	Nil	3.78	5.00	0.00220
D	1x4 (East)	103.850	103.992	-9.79	Nil	3.95	5.00	0.00196
D	2x4 (East)	113.433	113.583	-9.01	Nil	3.44	5.00	0.00180
D	3x4 (East)	146.033	146.192	-10.38	Nil	3.74	5.00	0.00208
D	4x4 (East)	134.117	134.200	-5.43	Nil	3.75	5.00	0.00109
D	5x4 (East)	124.558	124.408	10.26	Nil	3.92	5.00	0.00205

Table A3: Data for loading eccentricity
(A = Train station platform, B = Parking structure, C = Residential building and D = Office building)

Site	Grid location	Loading eccentricity (mm)
A	1x2	40.00
A	2x1	15.00
A	2x2	25.00
A	3x1	30.00
A	4x1	45.00
A	3x2	12.00
A	4x2	50.00
A	5x1	10.00
A	5x2	7.00
A	6x1	8.50
A	6x2	5.00
A	19x15	14.30
A	19x16	14.10
B	1x1	8.50
B	1x2	15.50
B	2x1	19.50
B	2x2	9.50
B	3x1	7.50
B	4x1	12.50
B	3x2	14.30
B	4x2	16.10
B	5x1	21.10
B	5x2	15.10
B	6x1	14.10
B	6x2	10.10
C	1x1	15.60
C	2x1	14.60
C	3x1	29.10
C	4x1	24.30
C	5x1	37.90
C	1x2	8.20
C	2x2	8.70
C	3x2	30.20
C	4x2	6.70
C	5x2	5.20
C	1x3	20.30
C	2x3	13.00
C	3x3	25.60
C	4x3	21.70
C	5x3	24.30
C	1x4	13.40
C	2x4	16.90
C	3x4	23.40
C	4x4	12.00
C	5x4	11.60
C	6x4	37.50
C	7x4	14.90
C	8x4	22.30

Site	Grid location	Loading eccentricity (mm)
C	9x4	9.60
D	1x1	15.00
D	2x1	21.00
D	3x1	8.70
D	4x1	6.90
D	5x1	16.40
D	1x2	18.30
D	2x2	22.70
D	3x2	5.70
D	4x2	19.30
D	5x2	16.70
D	1x3	15.20
D	2x3	15.00
D	3x3	20.90
D	4x3	47.60
D	5x3	11.80
D	1x4	29.90
D	2x4	15.00
D	3x4	18.30
D	4x4	13.50
D	5x4	4.60
D	6x4	10.40
D	7x4	11.60
D	8x4	24.20
D	9x4	11.90
D	10x4	51.50