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SS580:2012 Code of Practice for Formwork and Some Related Issues

by Dr N Krishnamurthy, Structures and Safety Consultant, Singapore

Three events are of significance in relation to formwork safety in Singapore. They are:

- *Implementation of SS580:2012 Code of Practice for Formwork in 2012 [Ref 1]*
- *Solutioning Session on Preventing Formwork Incidents, organised by Workplace Safety and Health Institute (WSHI) and held on 28 March 2014 [Ref 2]*
- *IES Seminar on Formwork Safety, held on 29 September 2015*

Having participated in all three of these events, the author wishes to share his experiences and thoughts on these events and related matters.

A fourth related event, of considerable personal significance to the author, was the one-day course on SS580:2012 organised by IES and held on 23 September 2014. The course was developed and presented by the author, with Dr Gan Siok Lin, Director of WSHI addressing the first batch of participants.

In addition, the Ministry of Manpower (MOM) came out with the two following circulars on formwork safety:

- *Circular on Safety Requirements for Formwork Structures, 31 January 2013 [Ref 3]*
- *Advisory For Professional Engineers On Formwork Safety, 18 January 2014 [Ref 4]*

DEFINITIONS

Some definitions are presented below and illustrated in Figure 1.

'Scaffold' is the structure that provides the working platform for workers, their tools, and some materials, to facilitate the erection of the permanent structure like a building or bridge.

'Formwork' is the mould into which concrete and steel reinforcement are placed and allowed to harden and cure. Once the concrete has gained sufficient strength to support its own weight and other construction loads, the formwork may be removed, unless occasionally it is left in place to constitute part of the permanent structure.

'Falsework' is the support for the formwork, transferring loads to the base in the same manner that the scaffold transfers the worker loads. 'Formwork Structure' is the combination of formwork and falsework. In casual use, the term 'formwork' or simply 'forms' may be used to refer to the formwork structure.

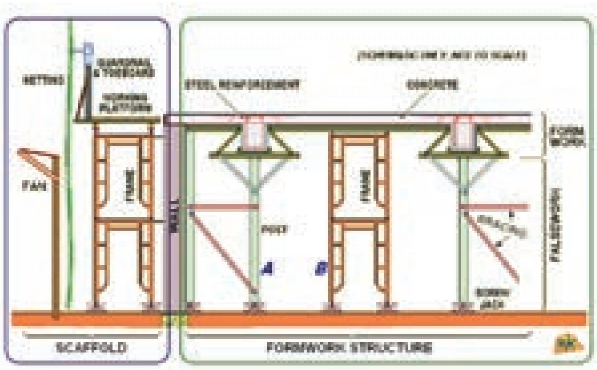


Figure 1: Scaffold and formwork structure terminology

CAUSES OF FORMWORK FAILURES

In recent years, there has been a spate of formwork failures, which reinforces the need for stricter compliance with SS580:2012 Code of Practice for Formwork. Findings of investigations into these and other failures are summarised below.

MOM'S 'OPERATION CARDINAL'

This inspection exercise in 2012 highlighted a number of hazards in formwork erection and use, as shown in Table 1 [Ref 5].

WSHI SOLUTIONING SESSION

The review report [Ref 2] by WSHI in 2014, on this topic, details the causes of formwork failures in Singapore. Table 2 provides a summary.

A total of 66 stakeholders attended the WSHI Solutioning Session, comprising participants from Formwork Suppliers, Main Con-

No.	Observations	Remarks
1	Poor fall prevention/ protection	• Missing or ineffective barricade/guarding
		• Improper access on reinforced bar cages
		• Inadequate clearance height for fall protection
		• Improper securing of life line to reinforced bar
2	Unsafe working platforms	• Unsecured metal decking used as temporary work platforms
3	Unsafe access & egress to formwork	• Improper and unsafe access/egress
		• Poorly erected access/egress
4	No PE design & Certificate of Supervision (COS)	• Formwork structure for casting beams of thickness ≥ 300 mm not designed by PE
		• Formwork not inspected by PE before casting
5	Formwork system used as scaffold	• Formwork shoring misused as a scaffold system
		• System not type approved by MOM
6	Poor site documentation system	• No or inadequate formwork documentations available
7	Poor supervision	• Lack of supervision by formwork supervisor

Table 1: MOM findings from Operation Cardinal

Item	Factor involved	Deficiency
1. Lack of Competency	(a) Workers	Inadequate training
	(b) Supervisors	Inadequate understanding
		Insufficient number of supervisors
		Inadequate supervision
	(c) Professional Engineers	Inadequate appreciation of loadings
	(d) Project Managers	Lack of management experience
2. Lack of Communication	(a) Engineers & Architects	Lack of coordination during design
	(b) Professional Engineers	Lack of coordination leading to incompatibility of formwork structure
	(c) All Stakeholders	Lack of common forum for discussion
		Lack of guidance in erection and contractual requirements
3. Poor Resource Management	(a) Materials	Illegal mixing of components from different systems
		Improper installation in tight spaces
	(b) Time	Insufficient time for PE to inspect
	(c) Manpower	Lack of PEs to inspect
		Lack of supervisors to stay and supervise a single job

Table 2: Causes of formwork failure

tractors, Formwork Contractors, Formwork Supervisors, Formwork Trainers, Project Managers, Professional Engineers, WSH Professionals, Architects, Academia and Government Bodies.

GENERAL CAUSES OF FORMWORK COLLAPSE

Under-design and over-loading

In theory, formwork must be designed so that it will be strong and stable under construction loads which should include delivery of cement bags, concrete and rebar bundles.

A bundle of 20 numbers of 15 m long 32 mm rebars weighing about 19 kN may be placed on formwork designed for 1.5 kN/m^2 plus a slab load of 8 kN/m^2 – which would certainly lead to collapse.

It will not be economical for the formwork structure to be designed to take the heaviest loading anywhere on it. The concrete and rebar weights themselves, acting as live loads on the temporary structure (which will become load-resisting 'dead-load' members in the permanent structure) are by themselves quite heavy.

But often, heavier loads like cement bags and rebar bundles, and pumps, vibrators or other erection machinery would have to be placed on the formwork. These will be as heavy as or heavier than the concrete and rebar loads.

Hence, certain parts of the formwork would have to be designated as 'heavy-load' zones. Heavy loads must be placed only at these specially designed, designated zones, spread over a wide area by means of planks, placed on or close to extra supports underneath.

These designated heavy-load zones must be clearly marked on the drawings as well as at site (as with 'H' in Figure 2), to enable crane operators to place the heavy loads at the appropriate locations and not inadvertently load the formwork structure to collapse.

In practice, due to a lack of clear instructions, the design may not cover construction loads. On the other hand, in haste or due to a lack of understanding and control, heavy loads may end up being placed at locations not specifically designed for the heavy loads. Collapse will occur in both cases.

Figure 2: Heavy load zone marked 'H'.

Safe Work Procedure

At site, Safe Work Procedure (SWP) may not cover alternative means to keep loads within safe bounds. SWP must specifically cover the infrequent and unusual tasks at site, as follows:

- Prior arrangements made to open bundles at ground level or on strong bases and distribute them on formwork, may not always be followed.

  - A designer may assume that a bundle of rebars resting on a formwork will be a uniformly distributed load. But the crane cannot deliver the rebar bundle on to the formwork precisely flat so as to ensure a uniform distribution of total load.

  - One end or the other may touch the formwork first, when at least half the weight amounting to about 10 kN will be delivered as concentrated load to the formwork, over-loading the temporary structure, at least temporarily.

  - To prevent this, the design and related SWP must specifically cover placement of heavy loads on formwork.

- Formwork is most unstable and at its weakest during concrete casting and in the early stages of hardening and curing. There are rules for placement of concrete on form-work, for height of drop, and spread area.

  - SWP must specifically address this task.

- In multi-storeyed buildings, SWP must also cover shoring of new work above recently completed work which may not have attained adequate strength, or may not itself be adequately shored. In such cases, the Engineer should be consulted.

Buckling of compression members

Many failures of formwork have been traced to buckling failure of slender compression members which may include both vertical columns and inclined or horizontal struts.

Tall and slender compression members buckle – that is snap into a curved shape, shed load, and collapse – suddenly and without warning when loaded to their critical value. The critical loads fall sharply with increasing slenderness.

Often, the material remains elastic so that when the load is removed, the column may spring back to its original shape.

Theoretical critical buckling stress on a column is given by the Euler Formula:

$f_{cr} = \pi^2.E.r^2/L_E^2 = \pi^2.E/\lambda^2 \leq f_y$, where

λ is Slenderness ratio = (L_E/r), L_E being the unbraced length, r being the radius of gyration = $\sqrt{(I/A)}$, I being the moment of inertia and A being the cross-sectional area, E is the Young's Modulus of Elasticity for the steel, and f_y is the yield stress for the steel.

Practical values of critical load $P_{cr}(=A.f_{cr})$ further depend on:

- End support conditions
- Intermediate bracing

Figure 3 depicts theoretical and practical stress levels in columns for various slenderness ratios.

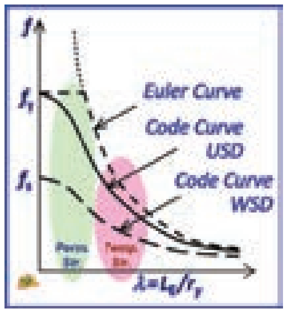


Figure 3: Euler, practical curves

Most permanent columns are designed to take 60% to 80% of permissible stress, while temporary struts, being long slender elements with no in-fills or moment resistance at the connections, can take only 40% to 60% of the permissible stress. These zones are shown as shaded ovals in the figure.

While the ends of struts may be free, pinned, or fixed, only the 'both ends pinned' condition provides the feasible and economical support for temporary structures.

The influence of intermediate lateral bracing on column capacity is indeed awesome, as depicted in Figure 4. When one lateral support is provided, splitting the total height into two equal parts, the capacity increases to four times. With two lateral supports dividing the height into three equal parts, the capacity increases to nine times. Capacity increases as the square of the number of braced parts into which the member is divided.

What should be frightening is the reverse argument. If a single mid-height support is removed, the capacity drops by 75% of designed value. If one out of the two intermediate supports is removed, the capacity drops by about 55%.

Higher strength materials (especially steel) lead to two penalties on buckling. One, the higher strength will naturally lead to smaller areas which generally increase the slenderness ratio resulting in lower capacity. Two, yield strength of the steel itself shows up as an adverse factor in increasing the slenderness effect.

So, beyond a certain point (such as 460 MPa), higher strength would make the buckling situation worse.

Without going into details, the following may be said about slenderness ratios:

- Hollow sections are better than solid sections.
- Best to worst cross-sections: Circle → Square → Rectangle → 'I' → 'T' → Channel → Angle
- Unsymmetrical sections have a strong axis and a weak axis (Figure 5), with quite large differences in the radii of gyration about these axes, so that the weak axis capacity may be many times smaller than the strong axis capacity.

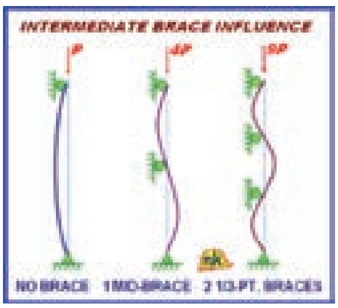


Figure 4: Intermediate bracing

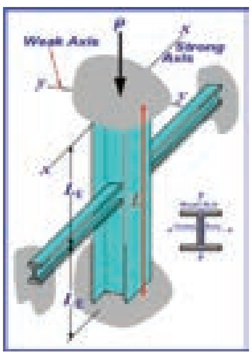


Figure 5: Weak axis support

- To increase the weak axis capacity, one or more intermediate supports may be provided to resist buckling about the weak axis (as shown in Figure 5).

Inadequate bracing for falsework

Another major cause of formwork failure is lack of or inadequate bracing against instability and sway. Instability is due to buckling of long, slender compression members discussed in the previous sub-section. Sway is the lateral shifting away from the original designed position under vertical and/or horizontal loads, again causing collapse. The following points should be read with reference to Figure 6:

(a) As mentioned in the previous sub-section, tall slender columns buckle and collapse.

(b) Columns under horizontal or eccentric vertical loading tend to sway sideways, unless prevented from swaying.

(c) Buckling and sway can combine to collapse one or a set of columns.

(d) Buckling capacity may be increased by providing lateral support at intermediate points along the length of the column. This support may be provided externally from existing permanent structures or other guys and anchors as at A and B in Figure 6(d). This external support system will also prevent side-sway.

(e) Lateral support against buckling may also be provided internally by diagonal bracings as at C and D in Figure 6(e). This internal diagonal bracing system will also prevent side-sway, in the rows of panels with diagonal bracing.

(f) Internal diagonal bracing may take many forms, with the common characteristic that the diagonals must be in opposite directions in adjacent panels and/or adjacent rows.

(g) An alternate arrangement to (f).

(h) Diagonal bracing in opposite directions may be used within the same panel as at A, especially if adjacent panels or rows cannot be braced. It is recommended that at least one diagonal bracing such as BC, or preferably a pair of diagonals run from the bottom of one end to the top of another end, crossing two or more bays. The crossings of such long diagonals with horizontal or vertical members may be connected for greater stability.

(i) All diagonals sloping in the same direction is not recommended.

(j) Often, it is wrongly assumed that horizontal bracings can both improve buckling capacity and prevent sway. As shown, even with horizontal bracing ABC, the columns can buckle and sway because these are possible by the braces ABC simply shifting horizontally to the location A'B'C' without any change in length, and hence without introducing any new forces.

It is not necessary to brace all panels or even all bays or rows. Every second or third (or other num-

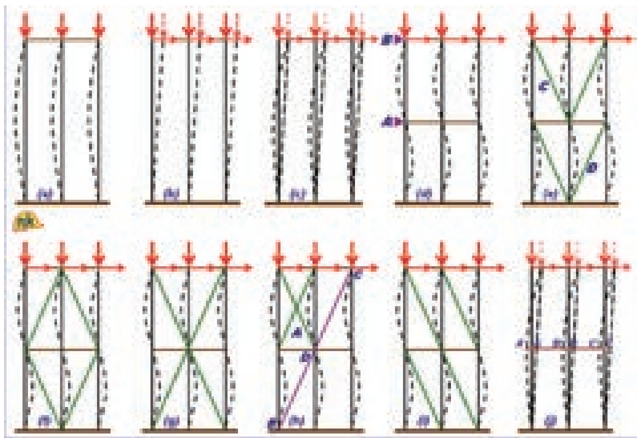


Figure 6: Buckling and side-sway in falsework, and ways of addressing them.

ber) bay or row may be braced, but the shears from the bays or rows with no bracing must be taken at the braced bay or row.

When a bracing is omitted or removed for any unavoidable reason, a competent person must check and confirm that this action does not introduce any instability in any bay or row. If it may be required, alternative bracings or external supports must be provided to prevent the instability.

Unsymmetrical sections will need more bracing about the weak-axis.

MAIN FEATURES OF SS580:2012 WORKING GROUP

In April 2010, the Working Group for Code of Practice for Formwork was constituted by the Technical Committee with the following composition:

Dr Ting Seng Kiong (Convenor)
Er. Chong Chin Hin
Mr C Kirubakaran
Ms Lee Guek Hoon (served until 23 June 2011)
Ms Koh Chin Chin
Er. Lim Chong Sit
Dr N Krishnamurthy
Er. Tan Chong Lin

The work was completed by the latter half of 2012, and the Code was approved in November 2012.

FACTOR OF SAFETY 2.0

SS280:5012 replaced CP23, the earlier Code of Practice. One of the significant differences between the two codes is the increase of the Factor of Safety to 2.0 from the average of 1.5 which was being followed according to BS5950 in use at the time. To justify this increase, we must analyse the differences between temporary and permanent structures and between formwork structures and scaffolds.

Permanent versus temporary structures

There is a common myth, or at least the common practice, that scaffolds and formwork structures are temporary, not a line item in client charges, and hence do not need and cannot afford as much attention or investment as the permanent structures that they help to build.

Nothing could be further from the truth! Time and again, it has been proved that temporary structures deserve at least as much consideration, in terms of design and safety, as permanent structures, and often even more. The argument will be along the following lines:

Unlike permanent structures, temporary structures

- do not have assured or well-prepared foundations
- are not designed as well or in as much detail
- are not used – or even seen – by the ultimate customer
- have often built-in compromises in quality and strength
- are put together at site from numerous components
- most components of which are already used and some are damaged
- are erected generally by less skilled temporary workers
- are not checked as rigorously or as frequently
- are not inspected as meticulously
- are not supervised as strictly
- are not maintained as well
- do not have their faults rectified as promptly or fully
- are the first to be compromised in terms of safety when time or budget presses hard.

That is why temporary structures need more care, more supervision, not less!

Scaffolds versus falsework

Even among temporary structures, one must distinguish between scaffolds which are designed for work platforms and falsework which is intended to support formwork for concrete and reinforcement. The latter needs even more care than scaffolds, for the following reasons:

- Scaffolds are generally for workers and tools while falsework is for formwork and concrete casting loads.
- Scaffold live loads are of the order of 1.5 to 2kN/m^{2,} while falsework live loads are mainly concrete and rebars weighing 26 kN/m^3, which even for a 300 mm depth slab works out to 8 kN/m^2.
- Scaffold work is generally dry, static work, while falsework is subject to wet, dynamic work of concrete casting and vibration, with very hazardous materials which will set hard within a short time.
- Scaffold erection is relatively better organised and more visible at all times than falsework which involves more components and variable sizes, more adjustments and actions, and components hidden from view.
- Scaffold failures may generally be localised while formwork/falsework collapse can be massive and progressive.

Applicability of Factor of Safety

The increased Factor of Safety, termed 'Safety Load Factor' to encompass both working stress and ultimate strength approaches, applies to any and all analysis and design of formwork structures. Specifically, it mandates as follows:

- Factor of Safety of 2.0 for yield stress in working stress method
- Load factor of 2.0 for all loads and loading conditions in ultimate strength method
- Ratio of failure or permanent deformation load to worst case service load to be 2.0 in any component or assembly test, with all testing conforming to the following:
  - Testing shall be resorted to only where no approved codes exist for the particular structure or component to be used, and where the structure or component is

too complex for practical generic analysis.

- When site commissioning tests are required, a validation certificate issued by a testing laboratory accredited by the Singapore Accreditation Council (SAC) or their Mutual Recognition Agreement (MRA) Partner shall be acquired before formwork erection can commence.
- In any case, the structure or component shall demonstrate a Load Safety Factor of 2.0 at structural or functional failure.
- For proprietary or contractor-proposed formwork structure, or components, the prototype structure or component, as complete in all respects similar to erection, use, and dismantling conditions at site as possible, shall be tested to no less than twice the worst combination of service loads.
- Erection, alteration, use, and dismantling of test components shall be done by personnel as similar to those available at site as possible.
- Testing shall be conducted under controlled conditions in an approved testing facility.
- A certificate and report shall be issued with all details, including how superimposed loads were simulated.
- Stress, deflection and sway histories shall be included.
- Test results may not be accepted if some valid theoretical analysis shows that the structure or component may not be able to take loading as claimed.
- Proration to 2.0 when any other code is used in the absence of applicability of SS580, where the factor is less than 2.0 in the other code
- Certification of the Factor of Safety for proprietary formwork products, and proration to 2.0 if the product's Factor of Safety is less than 2.0.

Thus, whatever product is used in formwork structure and whichever analysis, design, or test procedure is used to support its validity, there shall be a reserve of 100% between the worst service load and failure or permanent deformation load.

During the IES Seminar on 29 September 2015, a well-known manufacturer of formwork components made a presentation on how the company was addressing the requirements of the new code. The author hopes all manufacturers and suppliers will follow suit!

STABILITY IN SS 580:2012

To address the many deficiencies in formwork stability, SS580 includes a number of stipulations and guidelines, as follows:

Resistance to horizontal actions

The formwork structure shall be designed for safety, to ensure stability against overturning, uplift, sliding and side-sway, taking into account the sequence of construction under the action of the most adverse load combination. There shall be a minimum Factor of Safety of 2.0 against overturning and sliding.

In the absence of sufficient information on horizontal forces, horizontal forces equivalent to 2.5% of the applied vertical loads considered to act at the points of application of the vertical loads on the formwork shall be provided for.

When horizontal deflection exceeds 0.15 % of the height of falsework or other tolerance specified by the designer, the P-Δ effect of vertical forces shall be taken into account. These horizontal forces shall be transferred to a completed part of the permanent structure or sufficiently strong anchors.

Bracing for stability

Bracing shall be provided primarily to transfer horizontal forces to ground. Even where horizontal forces are transferred to anchors at the formwork level, bracing may be necessary to stabilise connections and reduce unbraced strut lengths.

Bracing shall be provided as necessary in all three planes of the formwork structure - longitudinal, transverse, and horizontal, as displayed in Figure 7.

- ABCD is the longitudinal plane for bracing, and LD is a diagonal brace in it.
- CDEF is the transverse bracing plane, and MJ is a diagonal brace in it.
- GHJK is the horizontal bracing plane, and NJ is a diagonal brace in it.

Falsework braces should be able to resist a minimum of 2.5% of axial force in the braced strut. For system formwork, documentation should include all bracing.

Temporary bracings may have to be designed and provided during erection and dismantling, to cater for unbalanced forces and to prevent excessive displacement or collapse.

Diagonal braces for multiple bays

Where bracings span more than one bay, the shears in the bays covered should be collected cumulatively and transferred to end anchors or the ground, with all crossing points being properly clamped.

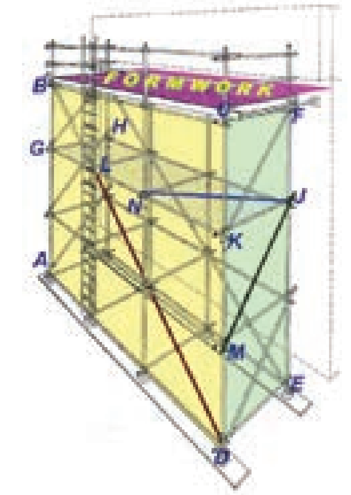


Figure 7:Three bracing planes

Braces intended to stabilise multiple bays shall be inclined between 30° and 60° to the horizontal, and shall preferably be in pairs, with each pair being inclined in the opposite direction to the other, to provide for change in the direction of applied forces.

SS580 suggests that there shall be a minimum of one pair of braces approximately for every 2h of vertical supports, where 'h' is the height covered by the brace, in metres. For example, if h is 4 m, one pair of braces may be used for every eight supports.

DESIGN CONSIDERATIONS

For steel, SS580 has adopted the EuroCode, along with the Singapore National Annex. However, there is one important stipulation in formwork design, that all load factors (which are widely variable in EuroCode for permanent structures) shall be taken as 2.0.

DESIGN LOADS

Allowance for heaping of wet concrete = casting layer depth

If concrete heaps to greater depth = Average Depth in 1 m^2

Live loads for personnel = 0.75 kN/m^2 over areas not occupied by concrete being cast, machinery, or equipment

Total imposed load i.e. wet concrete, personnel, machinery etc, not less than 1.5 kN/m^2.

Horizontal loads

- Lateral load of concrete dumping, wind etc not < 1.5 kN/m of floor edge, or 2.5% of total vertical load
- Lateral concrete pressure on form, p = w.H, where H is smaller of the depth of formwork or of concrete casting above the cold joint. The CIRIA formula that was in CP23 has been omitted because of the difficulty of controlling the parameters and because the formula was not applicable above 30° C. If someone wishes to use the CIRIA formula, they will have to demonstrate compliance with all requirements including the temperature criterion.
- Wind loads, to be as per SS CP14

In addition to the primary compression and bending checks, the code requires checking and satisfactory compliance of shears and deflections of the components.

DESIGN LIMITS

If and where this code does not cover any aspect of structural analysis or design of the formwork structure or any of its components, the relevant SS EuroCode and corresponding Singapore National Annex shall govern.

Where this code differs from SS EuroCode or Singapore National Annex, this code shall prevail.

Where no guidance is available from this code or the SS EuroCode and Singapore National Annex, and some other code is used, and the Safety or Load Factors in that code are less than 2.0, such factors shall be upgraded to 2.0.

Any and all proprietary or manufactured items used in the formwork structure shall satisfy the criterion of Load Safety Factor of 2.0 in actual use. The author suggests the following method to upgrade to the 2.0 Safety Factor requirement for a proprietary product.

Example of the use of a proprietary product with SS580

Suppose we want a section to carry 10 kN/m over a 3 m span. Let us say we have been using Company ABC's section 'T120' which proposes, according to its catalogue, that it be used for a 3 m span for load of 10.5 kN/m. Now on enquiry, the company may cite the Safety Factor against failure – with proper documentation – as 1.8.

To modify its use to comply with SS580, we may pro-rate the Factor of Safety from 1.8 to 2.0, by modifying the load capacity by the ratio 1.8/2.0 = 0.9, that is, reduce the load by (1– 0.9) i.e. 0.1 = 10%.

Then, the maximum load that can be placed on section over a 3 m span will be 10.5×0.9 = 9.45 kN/m, which is < 10 kN/m required – which is not good.

Note that this is the same as reducing the load capacity by 10%, i.e. 10.5×0.1 = 1.05, giving again, 10.5–1.05 = 9.45 kN/m – which is not good.

We now have to choose the next higher section, say 'T130', whose capacity may have been listed as 12 kN/m in the catalogue, for which, the SS580 adjusted capacity will be 12×0.9 = 10.8 kN/m, > 10 kN/m – which is acceptable.

This is also the same as increasing the service load by the ratio 2.0/ the cited value 1.8, that is, take the design load as (10.0×2.0/1.8) that is, 11.1 kN/m. Again ABC's 'T120' value of 10.5 kN/m will not suit, but 'T130' with 12 kN/m will.

An alternative would be to reduce the support spans to bring up the Safety Factor to 2.0. But this would involve the nature of the loading. For instance, the reduction would be (1.8/2) i.e. 0.9 of span for concentrated load, but $(1.8/2.0)^2$ i.e. 0.81 for uniformly distributed load.

GENERAL DESIGN PROCEDURE FOR COMPRESSION MEMBERS

The code stipulates that the following shall be assumed and implemented unless the contrary can be proven and implemented:

- All compression member ends are pin-ended and fabricated to be displacement-free at supported ends.
- All connections are pinned and non-moment-resistant.

As in SS580, there is no distinction between working stress design (WSD) and ultimate strength design (USD) approaches, a designer may use either of the following methods and arrive at the same answer:

- WSD: Take the worst case service load as the design load P, and determine a cross-section which will not be stressed more than the limiting stress value (f) of half the yield stress, or

- USD: Take twice the worst-case service load as the design load P, and determine a cross-section which will not be stressed more than the limiting stress value (f) of yield stress.

To be on the safe side, stick throughout to one or the other method in any single project!

Design of compression members is generally an iterative process and not a one-shot solution, simply because the critical buckling stress depends on cross-sectional properties which will be known only after design. The usual procedure is as follows, keyed to Table 3:

- Assume a starting stress value between half and one-third of limiting stress value, say 'f'.
- Find area 'A' required as (P/f), and select a section which would give the required area.
- Find the critical buckling stress f_{cr} for the chosen section.

  - With rolled steel sections, the section width and depth ratio, the component length to thickness ratio, whether strong or weak axis bending, and the material yield stress, will influence the limiting stress. These are addressed by means of Table 3 which will direct the user to use one or the other of five curves, corresponding to five 'imperfection factors' which enter the formulae on which the curves are based.

  - SS580 provides three options for finding the critical buckling stress f_{cr}, namely (i) Formulae and coefficients, (ii) Charts for the five different imperfection factors, and (iii) Tables from which intermediate values may be interpolated.

  - Find the Slenderness Factor 'λ_c' (lambda) from the formula, select the curve which applies to the section chosen, calculate, or from the particular curve in the chart, read off the Critical Stress Ratio 'χ_c' (Xi).

  - Then, the critical stress $f_{cr} = \chi_c.f_y$.

- If f_{cr} is more than 2f in the WSD approach or more than f in the USD approach, the chosen section is safe. If the difference is too much, a smaller size may be tried.
- If f_{cr} is less than 2f in the WSD approach or less than f in the USD approach, the chosen section is unsafe, and a larger section must be tried.
- The process is continued until a section's capacity matches or just exceeds the design load.
- Some finesse, learnt by experience, may be used to reduce the number of iterations.

  - If you assume 80 MPa as permissible stress and the actual limiting stress turns out to be 20 MPa, there would be no point in repeating the cycle again with 20 MPa, because we know that the result will shoot up. So a wiser move would be to take something between 80 MPa and 20 MPa for the second try, say the average of 50 MPa.

  - Rather than blindly checking the stresses and revising the section, it would be worthwhile to check the load capacity from (A.f) because a little shortfall in the stress may be compensated by a larger area.

  - Likewise, it is not just the area that influences the limiting stress. The key factor in buckling is the radius of gyration r [=√(I/A)]. So, in every revision, check if you can retain the same A with increased r, as for instance from a pipe with larger diameter but thinner wall thickness.

  - When nearing convergence, it is better to give up the stress-check approach, and simply choose the next bigger or smaller section. You will never get the exact capacity you need and will be invariably picking a section as close to but somewhat more than required capacity.

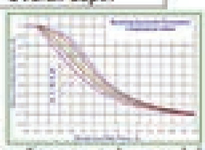
- Considerable savings may be obtained by trying to place additional lateral supports to vertical standards as long as enough working clearance (say 3 or 3.5 m) is provided at the base level for workers to move around with materials and tools.

Section buckling about strong axis and/or weak axis	S235 to S420		S460	
	Strong	Weak	Strong	Weak
Rolled 'I', with $h/b > 1.2$, $t_f \le 40$	a	b	a_0	a_0
(i) Rolled 'I' with $h/b > 1.2$, and t_f 40-100 (ii) Rolled 'I' with $h/b \le 1.2$, and $t_f \le 100$	b	c	a	a
Rolled 'I' with $h/b \le 1.2$, and $t_f > 100$	d	d	c	c
Welded 'I' with $t_f \le 40$	b	c	b	c
Welded 'I' with $t_f > 40$	c	d	c	d
Hollow, hot finished	a	a	a_0	a_0
(i) Hollow, cold formed (ii) Welded box with weld leg > $t_f/2$, $b/t_f < 30$, $h/t_w < 30$ (iii) Channel, 'T', or solid	c	c	c	c
Welded box, except as in (ii) above, or angle	b	b	b	b
b = Overall width, t_f = Flange thickness, t_w = Web thickness, h = Overall depth				

$$\chi_c = \frac{1}{\phi + \sqrt{\phi^2 - \lambda_c^2}} \text{ but } \chi \le 1 \text{ where: } \phi = 0.5\left[1 + \alpha(\lambda_c - 0.2) + \lambda_c^2\right]$$

$$\lambda_c = \frac{\sqrt{f_y}}{1440}\left[\frac{L_{ex}}{r_c}\right]$$

curves



and, α is an imperfection factor = 0.13, 0.12, 0.34, 0.49, and 0.76, for sections a_0, a, b, c, and d

Table 3: Buckling curves applicable to various sections in compression

GENERAL DESIGN PROCEDURE FOR BENDING MEMBERS

Bending members, especially of thin-walled metal sections, have an additional complication of lateral torsional buckling (Figure 8) which will involve a bending capacity calculation as follows:

$$M_{cr} = C_1[\pi^2 EI_y/L^2]\sqrt{[(h-t_f)^2/4 + (L^2 GI_t)/(\pi^2 EI_y)]}$$

Although the expression is 'frightening', all the terms are known and sectional dimensions are tabulated.

The general procedure for design is quite similar to that for compression members, with a similar table and set of five curves (this time grouped as rolled and welded sections) or coefficients available as shown in Table 4.

DESIGN FOR NON-STEEL MEMBERS

Members of wood, plastic, aluminium or any other non-steel material shall be designed by applicable Singapore Standards or other relevant codes/regulations, or shown by generic methods or tests to be satisfactorily designed.

All such designs shall be demonstrated to have a Load Safety Factor of 2.0 against collapse under the worst design loading. If any code adopts a Factor of Safety less than 2.0, its formulae, charts, tables etc shall be pro-rated to give a Factor of Safety of 2.0.

SPECIAL CASES FOR DESIGN

Special attention shall be paid to design and erection of formwork components by the Engineer in the following cases:

- Cantilever spans
- Heights exceeding 9 m
- Slabs thicker than 300 mm or as per regulation whichever is more stringent
- Beams exceeding cross-sectional area of 0.5 m^2 or as per regulation whichever is more stringent
- Columns or walls exceeding 2 m in height
- Formwork structure in two or more tiers
- Layer casting of concrete, for which, unless the sharing of subsequent layer loads by supporting columns is justified by calculations, the entire layer load shall be borne by the formwork structure
- Working platforms for formwork, designed and erected independently of the formwork and the reinforcement on it

  - However, where working platforms form part of integrated formwork systems such as climbing forms or table forms, scaffold regulations in force will apply to the working platform extensions.

KNOW YOUR MATERIAL

Both designer and fabricator must know what the strength of the formwork material is so that a Factor of Safety of not less than 2.0 can be obtained.

Particularly in wood, the designer must specify and occupier must receive the particular grade of wood chosen. Many users do not know the strength of the grade of timber they are using.

Table 5 shows that timber strength (according to BS5268) can vary from 2.8 MPa to 20.5 MPa. It illustrates how dangerous it would be to use a grade that is two classes lower than designed, and conversely, how wasteful it would be to use a grade that is two classes higher.

Developers and contractors must insist on specifying the grade to designers and receiving that grade from the vendors.

As already mentioned, chasing high strength steel may not always be good. Higher strength will mean less material, but it will also reduce buckling capacity.

SAFETY CONSIDERATIONS

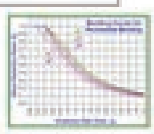
SS580 provides extensive guidelines on safety, highlighting many items

Figure 8: Lateral torsional buckling

Section buckling about strong axis and/or weak axis	Limits	Curve
(i) Rolled doubly symmetric 'I' and 'H' (ii) Hot finished hollow sections	$h/b \le 2$	b'
	$2.0 \le h/b \le 3.1$	c'
	$h/b > 3.1$	d'
Cold formed hollow sections	$h/b \le 2$	c'
	$2.0 \le h/b \le 3.1$	d'
Angle, for moments in major principal plane		d'
All other hot-rolled sections		d'
Welded doubly symmetric sections	$h/b \le 2$	c
	$2.0 \le h/b \le 3.1$	d
b = Overall width, h = Overall depth		

$$\chi_{LT} = \frac{1}{\phi + \sqrt{\phi^2 - \beta\lambda_{LT}^2}} \quad \text{but } \chi_{LT} \le 1 \quad \text{where: } \lambda_{LT} = \sqrt{(W_y f_y/M_{cr})}$$

and $\phi = 0.5[1 + \alpha(\lambda_{LT} - \lambda_{LT0}) + \beta\lambda_{LT}^2]$



α is an imperfection factor = 0.34, 0.49, and 0.76, for curves b, c, and d;

Coefficient λ_{LT0}, the λ_{LT} value up to which χ_{LT} = 1: Rolled = 0.4, Welded = 0.2; and,

Coefficient β, correction factor: Rolled = 0.75, Welded = 1.

Table 4: Lateral torsional buckling curves applicable to various sections

that can go wrong and suggesting solutions.

RISK ASSESSMENT

On the matter of Risk Assessment (RA), which is very critical for formwork structures, SS580 refers to the Code of Practice for Risk Management [Ref 6].

However, MOM, in its Circular of 2013 [Ref 3] lists the items that should be considered, among others, as follows:

- Formwork structure erection, alteration and dismantling procedures
- Base support capacity
- Formwork structure stability
- Placement of rebar
- Concrete casting
- Working at height
- Monitoring of formwork
- Formwork leakage
- Formwork structural failure
- Settlement of formwork structure
- Repair of formwork structure
- Emergency escape route
- Emergency response plan

SAFE WORK PROCEDURES

Safe Work Procedures (SWP) shall be written soon after RA. Apart from method statements for routine work, SWP should include responsibilities of all stakeholders, Personal Protection Equipment (PPE) to be used and emergency measures.

SWP should cover all anticipated activities during the work, particularly the infrequent and unusual ones. They shall be strictly followed and all PPE should be correctly worn all the time the workers are carrying out their tasks.

WORK AT HEIGHT

Work at height is unavoidable in most formwork activity and special safeguards shall be implemented to avoid accidents such as falling from height. All criteria should be checked and all requirements fulfilled as in the Code of Practice for Safely Working at Height [Ref 7]. A fall prevention plan must be prepared and followed by the occupier of the workplace.

Strength Class	Bending Strength N/mm²
SC1	2.8
SC2	4.1
SC3	5.3
SC4	7.5
SC5	10.0
SC6	12.5
SC7	15.0
SC8	17.5
SC9	20.5

Table 5: Timber strength

MODULAR AND SYSTEM FORMWORK

Persons involved in erection of these systems shall be trained in safe erection, alteration and dismantling of the system, as well as inspection criteria such as defects precluding use of certain materials and components. System formwork suppliers shall provide documented instructions and training on erection, use, transfer, alteration and dismantling of the formwork system.

The training should include, but not be limited to, the following:

- Maximum loadings that can be applied to various areas of the form, with areas of heavy loadings and the material storage specifically designated on drawings and the actual formwork
- Restricted access areas and procedures for erection and removal of edge protection
- Emergency evacuation procedures for those required to work on the form.

SAFE FORMWORK CONSTRUCTION RELATED TO DESIGN

Safety aspects shall be considered and controls implemented at every stage in the life-cycle of the formwork structure, including planning and inspection, and during construction. Some common measures for good construction practice to ensure safe formwork design, in addition to those already mentioned, are as follows:

- Provide adequate shoring or re-shoring.
- Avoid using a prop directly on top of another prop.
- Ensure that adequate temporary bracings are in place while setting up the formwork.
- Ensure that anchoring of the system formwork can be visually ascertained.
- Ensure adequate provision for lateral pressure on forms.
- Control lateral pressure on forms by vertical rate of concrete placement by adjustment of slump, type of vibration, admixtures etc.
- Regulate horizontal sequence and rate of placing concrete to avoid unbalanced loading on the formwork structure.
- Control loadings that may cause vibrations and shock.
- Prevent premature removal of supports.
- Comply with recommendations of manufacturers of components and keep within limits set by the designer.
- Ensure proper field inspection by formwork supervisor to see that form design has been properly interpreted and implemented by the formwork erectors.
- Ensure that formwork components, not designed by analytical methods or not certified as safe by suppliers, are validated for use by testing.
- Ensure that interactions between formwork, falsework and permanent structure are taken into account in planning and construction.
- Provide safe means of access, adequate edge protection, perimeter containment screening etc, to ensure a safe work zone.
- Provide temporary catch platforms as fall arrest for fall distances shorter than required for body harnesses.
- Disallow any field repair of modular or system formwork components without manufacturer's approval.

- Provide cable-guided or supported systems with integral free-fall breaking devices.
- Disallow use of form panels such as from wall or column formwork, for purposes other than those for which they were designed for, such as ladders, walkway bridges etc.
- Ensure specific industrial standards are observed for hydraulic and electrical equipment used for operating system formwork.
- Ensure rotation of workers, rest periods, and other safeguards against fatigue and Musculo-Skeletal Disorders (MSD) due to repetitive work.

SAFETY-RELATED CONCERNS IN FORMWORK ACTIVITIES

Among the many hazardous activities and situations in formwork erection, use, alteration and dismantling, the following deserve special attention:

- Movement of vehicles at the entrance to and within the site
- Movement of large and heavy objects, involving cranes, fork lifts etc
- Manual handling of heavy objects conforming to relevant regulations limiting the load to be lifted by a worker on a regular basis to 25 kg
- Ergonomic hazards in general, which may lead to MSD
- Working at height, for which various measures for fall prevention such as edge protection, and work restraint should be adopted first rather than fall arrest measures such as body harness, or catch net
- Working in confined space, in tunnels or other areas where natural light and ventilation are not available, for which various measures such as toxic gas and oxygen deficiency checks and rescue systems should be implemented
- Storage and handling of hazardous materials such as:

  - Chemicals used in formwork erection and oiling
  - Cement, which is corrosive to the skin and damages eyes and lungs
  - Abrasive or sharp-edged objects
- Noise leading to Noise-Induced Deafness (NID)
- Unsafe acts and unsafe conditions arising from extensive human intervention and the simultaneous interaction of many trades, requiring strict and often continuous supervision at every stage of erection, use, alteration, and dismantling of formwork structures
- When various types of works by steel fixers, plumbers, electricians, and other trades are ongoing, strict segregation of the formwork construction zone and the zone for other trades
- Impact of vehicles / machinery adjacent to formwork structures

CONCLUSION

Formwork structures have been in the news in recent years for the wrong reasons, with reports of numerous collapses, injuries and fatalities. The new Code SS580 may not solve all the problems but will hopefully eliminate the risks of under-design, over-loading, and inadequate workmanship and supervision, as causes of the accidents.

Formwork design by the EuroCode should be much simpler than for permanent structures, although it may be marginally costlier than earlier. However, the increased cost will be spread over multiple uses of the components, and in due course will pay off in improved safety, with consequently decreased expenses and compensation as well as disruption of work from accidents.

One last piece of advice: An unwritten but irrevocable law is "Ignorance of the law is no excuse". What this implies is that if after an accident, the investigation reveals that it happened due to the violation of a law or laws that were required to be followed, the responsible person(s) cannot plead ignorance of those laws as a reason for their not implementing them.

In practical terms, it means that although SS580:2012 is one of the few standards for which one has to pay, it would be wise to buy a copy, at a cost of S$36, and circulate it to those who must deal with formwork design, erection, use, or dismantling, so that any violation cannot be hidden behind administrative lapses.

(More information on the author and his work can be obtained from www.profkrishna.com).

REFERENCES

[1] SS580:2012, Singapore Standard Code of Practice for Formwork, SPRING Singapore, 2012, 40 pp.

[2] 'Preventing Formwork Incidents – Report on 28 Mar 2014 Solutioning Session', WSHI, Singapore, July 2015, 8pp.

[3] Circular on Safety Requirements for Formwork Structures, 31 Jan 2013, 9 pp.

[4] Advisory For Professional Engineers on Formwork Safety, 18 Jan 2014, 4 pp.

[5] Ng, Anderson: 'WAH Enforcement Findings on Formwork Erection – Operation Cardinal', MOM, Singapore, 20 Jul 2012. Retrieved (in 2014) from: https://www.wshc.sg/wps/themes/html/upload/event/file/2012/WAH%20Enforcement%20Findings%20by%20MOM.pdf

[6] Code of Practice on WSH Risk Management: 2011, Revised 2015, WSH Council in collaboration with the Ministry of Manpower, Singapore, 31 pp.

[7] Code of Practice for Working Safely at Heights: 2009, Revised 2013, WSH Council, Singapore, 69 pp.