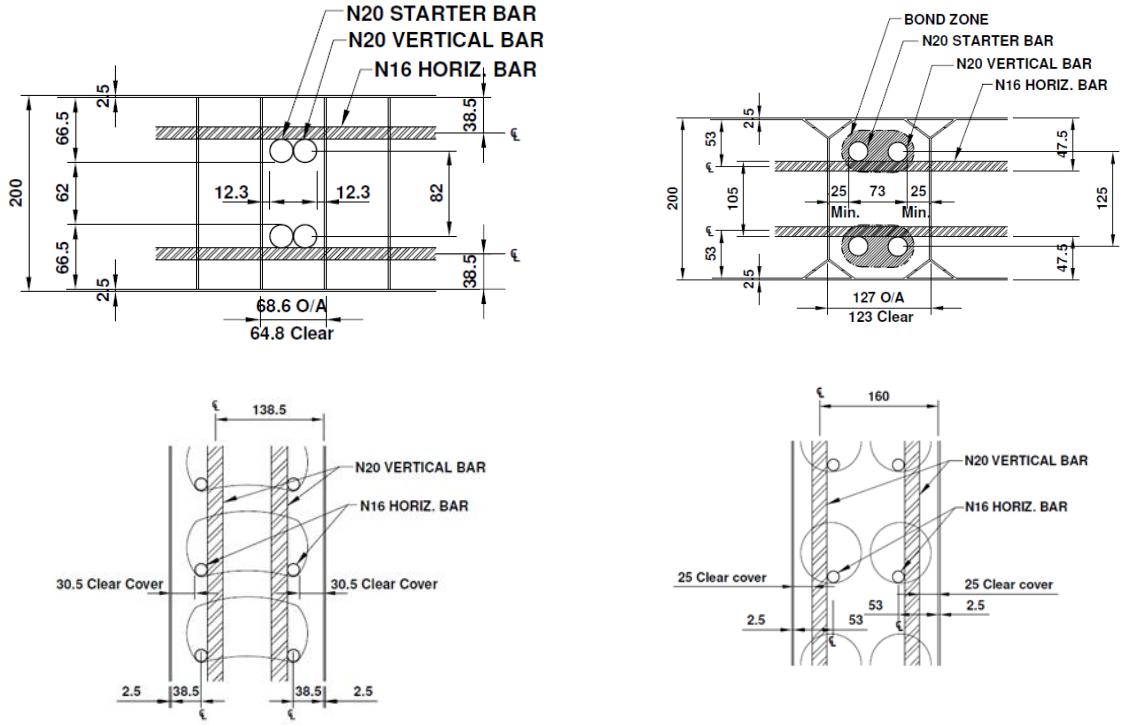
Technical Report: Comparative Assessment of Two Stay-in-Place PVC Wall Systems According to Structural Code Requirements

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This version of the report is the very final version, and all previous versions are superseded by this version. This report builds upon two previously issued technical reports on the comparative assessment of the two stay-in-place (SIP) PVC wall systems, dated 25/08/2025 and 21/01/2026. While incorporating the key analyses presented in those documents, the present report provides additional technical explanation and expanded discussion to further clarify aspects of the structural evaluation and code-compliance assessment. This study is conducted as a comparative evaluation of two distinct stay-in-place (SIP) PVC formwork systems, focusing on their performance against relevant structural code requirements. The evaluation emphasizes the influence of wall geometry — particularly the shape and spacing of cells — on code compliance and practical constructability. Both systems are examined under identical reinforcement configurations, featuring an overall wall thickness of 200 mm, with longitudinal N20 bars and transverse N16 bars. This common detailing facilitates a direct and meaningful comparison representative of typical design practice. Cross-sectional details for both systems are provided in Figure 1.



(a) System 1 (b) System 2

Figure 1 - Two PVC wall systems: (a) System 1 with smaller PVC cells (O/A 200 × 68.6 mm); (b) System 2 with larger PVC cells (O/A 200 × 127 mm).

The primary objective of this study is to assess whether these systems meet key structural design requirements, with particular attention to the Australian Standard AS 3600-2018. To ensure a comprehensive evaluation, additional international standards have been considered, including (See Appendices A, B and C):

- ACI 318-25: Building Code Requirements for Structural Concrete
- ACI 408R-03: Bond and Development of Straight Reinforcing Bars in Tension
- BS EN 1992-1-1:2023: Design of Concrete Structures (British Standard version)

In relation to practical constructability, the research by Gajda and Dowell (2003) is referenced to complement the code-based analysis with practical insights into concrete consolidation in similar SIP formwork systems.

Furthermore, consideration is given to construction site tolerances and the practical feasibility of achieving the specified reinforcement placement requirements in each system.

1. Lap Splice Length and Bond Performance in Stay-in-Place PVC Wall Systems

1.1. Overview of Relevant Standards

Concrete cover in reinforced concrete generally serves two primary functions: (i) durability protection, providing resistance against environmental degradation such as carbonation, chloride ingress, and moisture penetration; and (ii) bond and confinement capacity, which governs the ability of the surrounding concrete to resist radial splitting stresses, develop mechanical interlock, and transfer tensile forces from reinforcement into the concrete.

In this report, while the durability function of cover is acknowledged, the focus is on the bond and confinement role, which is assessed as the most critical parameter influencing lap splice performance and overall bond capacity of the reinforcement within the stay-in-place PVC wall systems. The American Concrete Institute (ACI) standards ACI 318-25 and ACI 408R-03, provide detailed guidance on lap splice length requirements and bond performance for reinforcing bars in tension. These requirements emphasize the influence of concrete cover and bar spacing on bond strength, confinement, and failure modes. Similarly, the Australian Standard AS 3600-2018 integrates confinement effects into lap splice length calculations through a confinement factor, dependent on minimum concrete cover and bar spacing, allowing optimized development length. In this study, **both contact and non-contact lap splice configurations** are examined within the context of the selected wall systems, using the same reinforcement detailing.

1.2. ACI 318-25 Requirements

1.2.1. Contact Lap Splices

For contact lap splices, bars placed directly in contact must have sufficient confinement through minimum clear spacing and concrete cover. The required lap splice length is a function of the development length per Section 25.5 of ACI 318-25. According to Table 25.4.2.3, which provides reference development lengths for different spacing, cover, and bar sizes:

- When bars are provided with adequate confinement—clear spacing and cover at least equal to the bar diameter (d_b) and minimum transverse reinforcement throughout the development or splice length—or when the clear spacing is at least $2d_b$ and the clear cover is at least d_b, the standard development length formulas apply.
- If the aforementioned conditions are not satisfied, the bars fall under the code's "other cases" category, for which the development length must be increased by 50% to compensate for reduced confinement and the risk of brittle splitting failures. It is noted that, according to ACI, the minimum clear spacing requirements of Section 25.2 and the minimum concrete cover requirements of Section 20.5.1.3 are mandatory.

1.2.1.1. Evaluation of Reinforcement Detailing: System 1 vs. System 2

- **System 1:** Longitudinal N20 bars are placed with a clear cover of only 12.3 mm due to PVC web intrusion, which is less than the minimum cover required by ACI 318-25 (Section 20.5.1.3). This condition is therefore not permitted by the code. If such reduced cover were hypothetically allowed, the splice would fall under the "other cases" category of ACI Table 25.4.2.3, requiring a 50% increase in development length.
- **System 2:** Provides clear cover more than d_b (approximately 25 mm) and clear bar spacing exceeding $2d_b$, fully satisfying confinement and spacing criteria. This configuration ensures proper concrete consolidation and bond behaviour without requiring splice length penalties.

1.2.2. Non-Contact Lap Splices

ACI 318-25 (Section 25.5.1.3) permits non-contact lap splices if the clear transverse spacing between bars is limited to 6 in (152.4 mm) or one-fifth of the lap splice length, whichever is smaller. The load transfer in such non-contact lap splices occurs through a continuous diagonal compression strut formed within the concrete between the bars. For this reason, the concrete between the spliced bars must be continuous and unobstructed to ensure effective load transfer.

1.2.2.1. Evaluation of Reinforcement Detailing: System 1 vs. System 2

- **In both Systems 1 and 2**, reinforcement placed in adjacent cells separated by PVC webs interrupts this continuous concrete strut, invalidating the non-contact lap splice according to ACI 318 and ACI 408R-03.
- **In System 1**, the shorter cell dimension (64.6 mm) does not provide enough space for a non-contact lap splice. Although the longer cell dimension in System 1 could theoretically permit the required spacing for a non-contact splice, this arrangement leads to suboptimal reinforcement positioning, reduces the effective moment arm, and is therefore not recommended as it would reduce the flexural strength capacity by 14%. Indeed, this option, would not satisfy AS3600 clause 11.7.3 – minimum 3 bar diameter requirement as this case would only provide 62 mm-2x20mm = 22 mm between the parallel bars.
- **In System 2**, when two N20 bars are placed within a cell measuring 195 mm × 123 mm, and a minimum clear spacing of 20 mm is maintained between the spliced bars, non-contact lap splices can be effectively used along the shorter cell dimension. This arrangement preserves the continuity of the concrete path and satisfies the requirements of ACI 318, ensuring full code compliance.

1.3. Australian Standard AS 3600-2018: Confinement Factor and Development Length

1.3.1. Contact and Non-Contact Lap Splices

The design principles for contact and non-contact lap splices are essentially the same, provided the clear spacing between bars remains within the code-specified limits. AS 3600-2018 incorporates a confinement factor into development length calculations (Clause 13.1.2.2), where:

$$k_3 = 1 - 0.15\frac{(c_d - d_b)}{d_b}, \qquad 0.7 \le k_3 \le 1$$

The confinement factor k_3 is a function of C_{min} , where C_{min} is defined as the lesser of the clear concrete cover and half the clear spacing between reinforcing bars. A well-confined region (large cover and spacing) may allow up to 30% reduction in development length, while poorly confined areas require increased lengths.

1.3.1.1. Evaluation of Reinforcement Detailing: System 1 vs. System 2

- **System 1:** With only 12.3 mm clear cover (less than the required minimum of 20 mm, which is the greater of bar diameter or max aggregate size), this system fails to meet minimum cover requirements (Clause 4.10.2). Insufficient cover compromises bond assumptions, making standard development length equations invalid. Although the panel contains intermittent openings along the webs, as shown in Figure 1 (a), providing greater cover in some regions, bond performance is controlled by the locations of minimum confinement. In this system, a typical one-metre lap splice includes approximately six 43 mm-wide zones where the concrete thickness adjacent to the bar is reduced to 12.3 mm. These reduced-thickness zones act as periodic weak points where radial splitting resistance is locally diminished, allowing cracks to initiate and propagate longitudinally, progressively undermining the effective bond capacity of the entire splice. This behavior reflects the mechanics of splitting-controlled bond failures, in which the weakest zones dictate overall performance. An analogy can be drawn to a chain: *its load capacity is governed by the weakest link, not the average strength of all links.* Similarly, the minimum confinement locations along a lap splice govern the initiation and propagation of splitting cracks, ultimately controlling the splice's structural capacity.
- **System 2:** Provides 25 mm clear cover, yielding a confinement factor of approximately 0.96, allowing a 4% reduction in lap splice length due to improved confinement, consistent with the standard.

For system 1, the development-length assessment correctly notes that the 12.3 mm concrete cover is insufficient. This is because the ability of a lap splice to safely transfer stress between reinforcement

and the surrounding concrete fundamentally depends on bond strength. Bond strength is not an arbitrary geometric preference; it is a mechanics-based requirement that ensures the tensile forces developed in reinforcing bars are reliably transferred into the surrounding concrete.

The Australian Standard AS 3600 is explicitly built on a comprehensive review of international test data and the accepted scientific principles incorporated in major codes such as ACI 318 and Eurocode 2. This is openly acknowledged in the AS 3600 Commentary (AS3600-2018 Supplement 1:2022 – Concrete Structures Commentary), which states that its development-length and bond provisions follow the same underlying methodologies as these international standards. For this reason, the technical report references ACI and Eurocode provisions.

A consistent concept across all reputable references is that a minimum concrete cover is required to ensure adequate bond performance. For example, BS EN 1992-1-1:2023 explicitly requires the concrete cover for bond to be at least one bar diameter.

In AS 3600, Clause 4.10.2 outlines how to determine minimum practical cover to allow concrete to be properly placed and compacted around reinforcement. The clause requires the designer to consider:

- the size and shape of the member
- the size, type and configuration of the reinforcement
- the aggregate size, workability of the concrete, and the direction of placement

The clause includes a deemed-to-satisfy (DTS) rule. The DTS provision within Clause 4.10.2 states that covers greater than the bar's nominal diameter or the maximum nominal aggregate size (whichever is larger) are deemed to satisfy the constructability requirements. A DTS provision, by definition, represents a code-accepted threshold below which the designer must positively and clearly demonstrate compliance through alternative means. This deemed-to-satisfy provision establishes a baseline minimum cover for constructability but does not restrict the designer from specifying larger cover where required for durability, structural performance, or bond. The AS 3600 Commentary further notes that larger covers may be necessary depending on detailing and performance conditions. Therefore, while Clause 4.10.2 primarily addresses constructability, sufficient concrete cover is mechanically essential to achieve reliable bond strength. As noted in the technical report, the 12.3 mm cover in System 1 compromises the bond zone and reduces the confinement necessary for development-length assumptions, making the actual bond performance unachievable.

1.4. BS EN 1992-1-1:2023: Influence of Cover on Lap Splice Design

BS EN 1992-1-1 follows the same fundamental concept as the American code (ACI 318) regarding the influence of concrete cover and bar spacing on lap splice design. Specifically, BS EN 1992-1-1 specifies a minimum concrete cover for bond. For separated bars, the minimum cover

is related to the bar diameter, as detailed in Table 6.5. Accordingly, System 1 does not comply with the code, since the cover provided is 12.3 mm for N20 bars, which is below the required minimum.

If such reduced cover were hypothetically allowed, reducing the concrete cover from 25 mm (System 2) to 12.3 mm (System 1) would result in a harsher bond condition, leading to approximately a 40% increase in the required lap splice length (Clause 11.4.2).

2. Impact of Longitudinal Rebar Position on Flexural Capacity

In evaluating the flexural capacity of the two wall systems, all key parameters—such as concrete compressive strength, rebar size and quantity, and confinement quality—are considered constant. The only variation lies in the location of the longitudinal tension reinforcement relative to the neutral axis.

As a simplified comparison, and neglecting the contribution of compression reinforcement, System 2 places the centroid of the tension reinforcement 160 mm from the extreme compression fiber, whereas in System 1 this distance is 138.5 mm (as shown in Figure 1 above). This difference results in approximately a 15% increase in flexural capacity due to the larger lever arm. The reason for the difference is the design of each system's web cut-outs and that during construction horizontal bars are placed first. To ensure minimum cover requirements are met, vertical bars in System 1 must be placed inside the horizontal bars leading to a lesser lever arm.

When the contribution of compression reinforcement is also considered, the increase in flexural capacity in System 2 will exceed 15% compared to System 1. This highlights how the optimal placement of longitudinal bars—particularly positioning them closer to the tensile face—can significantly enhance structural performance without altering other design parameters.

3. Influence of PVC Cell Dimensions and Concrete Workability on Consolidation and Practical Constructability Considerations

All international concrete design standards—such as those by the American Concrete Institute (ACI) and Eurocode—impose restrictions on bar spacing to ensure proper concrete consolidation. Similarly, the Australian Standard AS 3600 (Clause 11.7.3) specifies the minimum clear spacing between parallel reinforcement bars, requiring at least $3d_b$ (three times the bar diameter). This requirement is intended to reduce the risk of void formation, enhance concrete flowability, and maintain structural integrity.

In this context, both reinforcement layouts—System 1 and System 2—comply with AS 3600's spacing provisions. System 1, which uses longitudinal N20 bars with a minimum clear spacing of 62 mm, satisfies the code's minimum requirement. However, the relatively tight bar spacing limits the potential use of larger-diameter reinforcement. In contrast, System 2 provides a wider spacing of 105 mm using

the same bar size, offering not only greater compliance but also flexibility for accommodating larger bars, if needed.

A critical challenge in stay-in-place (SIP) PVC wall systems is the limited clearance between the internal PVC webs and the reinforcement. In System 1, the clear distance between the web and the longitudinal reinforcement is approximately 12.3 mm, whereas in System 2, this increases to about 25 mm. This wider clearance in System 2 significantly enhances concrete flow paths, facilitating consolidation and minimizing the likelihood of voids formation, especially when proper vibration is applied. Nevertheless, geometric configuration alone does not guarantee successful consolidation; other factors such as concrete workability, slump, and vibration method are equally influential.

In System 1, the smaller internal dimensions of the PVC cells limit the clearance available for placing reinforcement, especially starter bars. This makes it difficult to maintain the required tolerances and increases the risk of bar misalignment and congestion. Moreover, as mentioned in Section 1.3.1.1 of this report, Clause 4.10.2 explicitly requires designers to specify sufficient cover to enable satisfactory placement and compaction of concrete around the reinforcement (linking to Clause 17.1.3). The deemed-to-satisfy (DTS) provision provides a benchmark : covers greater than the bar diameter or maximum aggregate size are automatically considered adequate. The reduced 12.3 mm cover in System 1 does not meet this DTS threshold. In contrast, System 2 has larger cell dimensions that provide sufficient space for reinforcement placement, allowing for more accurate positioning. Additionally, System 2 incorporates a patented reinforcing steel placement clip for vertical bars, which further improves accuracy and constructability.

Considering other parameters such as concrete workability and slump, the findings of Gajda and Dowell (2003) from the Portland Cement Association offer useful insight. Their experimental investigation on Insulating Concrete Formwork (ICF) systems—which are conceptually similar to SIP PVC walls—showed that higher slump concrete, when paired with effective vibration, significantly improves consolidation, particularly in congested reinforcement zones. Notably, even in systems without internal webs, voids were observed near reinforcement when using low- to medium-slump concrete, underscoring the importance of mix workability.

In the current study, System 1 employs a concrete mix with a slump of 180 ± 20 mm and a maximum aggregate size of 10 mm. With the internal PVC webs located just 12.3 mm from the reinforcement, this arrangement provides minimal clearance, restricting concrete flow and increasing the risk of localized honeycombing. In contrast, System 2 utilizes a more workable mix with a slump of 220 ± 40 mm—categorized as medium-high in Gajda and Dowell's study—while maintaining the same aggregate size. Alongside the increased web-to-rebar spacing of approximately 25 mm, these conditions enhance concrete flow and substantially reduced the likelihood of voids.

Ultimately, while mix design and geometric layout are vital, the effectiveness of concrete consolidation in SIP PVC systems also depends on vibration technique and equipment. These parameters should be carefully selected and validated by manufacturers under various congestion scenarios to ensure consistent and reliable performance.

4. Summary and Conclusions

This comparative evaluation of two stay-in-place (SIP) PVC formwork wall systems demonstrates the distinct advantages of System 2 over System 1 in terms of structural performance and code compliance.

Key findings include:

- System 1 with only 12.3 mm clear cover (less than the required minimum of 20 mm, which is the greater of bar diameter or max aggregate size), fails to meet minimum cover requirements for concrete placement AS3600-2018 (Clause 4.10.2). Insufficient cover also compromises bond assumptions, making standard development length equations of AS3600-2018 invalid. The failure to be compliant by not meeting cover requirements will result in overstatement of the load-carrying capacity of the wall.

- System 1 concrete cover (12.3 mm) does not satisfy the minimum requirements of ACI 318-25, or BS EN 1992-1-1. Such detailing is noncompliant with the codes. Hypothetically, if such reduced cover were allowed, it would fall under the “other cases” category in ACI 318-25 or a harsher bond condition in BS EN 1992-1-1, requiring an increase in lap splice length of approximately 40–50% to compensate for the reduced confinement and bond strength.

- System 2 fully complies with concrete cover and bar spacing requirements as specified in AS 3600-2018, ACI 318-25, and BS EN 1992-1-1, providing optimal bond conditions and enabling reductions in lap splice length due to improved confinement.

- The larger cell dimensions in System 2 enable effective use of non-contact lap splices while maintaining continuous concrete paths, a requirement not met by System 1 due to its smaller cell geometry.

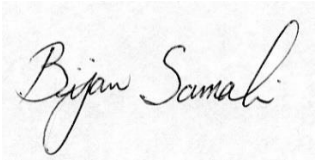
- The placement of longitudinal tension reinforcement farther from the compression face in System 2 increases the internal lever arm, yielding at least a 15% improvement in flexural capacity compared to System 1.

- System 2’s greater clearance between PVC webs and reinforcement, coupled with improved concrete workability, promotes superior concrete flow and significantly reduces the risk of

voids. Conversely, System 1's tighter bar spacing and limited web-to-rebar clearance raise substantial concerns about inadequate consolidation and localized void formation.

- The assessment of System 1 has been carried out on the basis of the starter bar and the vertical reinforcement bar being placed in an optimum position which itself results in the non-conformances noted above. If either bar is placed differently to the optimum position, then the non-conformances noted above will be exacerbated. System 1's relatively confined PVC cells make proper placement of reinforcing steel, as dimensioned, highly challenging. System 2's greater clearance between PVC webs, combined with patented reinforcement placement clips, ensures accurate positioning of reinforcing steel under typical construction site conditions.

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Appendix A – Relevant American Codes and Studies

- **ACI 318-25**: *Building Code Requirements for Structural Concrete and Commentary* – American Concrete Institute, 2025.
- **ACI 408R-03**: *Bond and Development of Straight Reinforcing Bars in Tension* – American Concrete Institute, 2003.
- **Gajda, J. and Dowell, A. (2003)**: *concrete consolidation and the potential for voids in insulating concrete form (ICF) walls* – Portland Cement Association.

Appendix B – Relevant Australian Standard

- **AS 3600-2018**: *Concrete Structures* – Standards Australia.
- **AS 3600-2018 Supplement 1:2022** – *Concrete Structures Commentary*

Appendix C – Relevant European Standard

- **BS EN 1992-1-1:2023**: *Eurocode 2 – Design of concrete structures – Part 1-1: General rules* – British Standards Institution.