3. DESIGN CONCEPTS

3.1 Strength Design

Behaviour in the Region of a Web Penetration

A large rectangular or circular penetration made in the steel web of a simply-supported steel or composite beam weakens the beam locally by reducing both the moment and shear capacities. This reduction in strength can be partly overcome by welding steel plates or flat bars to the web along the horizontal edges of the penetration as reinforcement. However, the economics of using web penetration reinforcement needs careful consideration.

In the absence of vertical shear force, the moment capacity of a beam cross-section at a large web penetration is reduced as a direct result of the loss of steel web area. Vertical shear force at the penetration gives rise to a more complex state of equilibrium as a result of Vierendeel action occurring over the length of the penetration. This action causes additional secondary moments to develop in the top and bottom T-sections. Its effect becomes more pronounced as the penetration length increases and as the shear-to-moment ratio increases, which explains why both of these factors need to be controlled during design.

The main features that become visible in the region of a web penetration at ultimate load are shown in Fig. 3.1. The most-highly stressed areas are located at the high- and low-moment ends of the penetration, denoted *HME* and *LME*, respectively. These features are briefly explained as follows.

The secondary moments may be sufficiently large to cause the slab to crack perpendicular to the steel beam, both in the top face at the *LME* and the bottom face at the *HME*. The combined effects of flexure, shear and Vierendeel action can lead to yielding in the top and bottom T-sections, and plastic hinges can form at their ends.

In many cases, large differential vertical deflection between the two ends of the penetration occurs when a major diagonal crack forms in the concrete slab directly above the penetration. This crack can lead to a sudden drop in the load-carrying capacity of the composite beam, significantly reducing its ductility [13]. Large tensile forces develop in the shear connectors at the *HME* region of the penetration [15], particularly prior to the onset of the diagonal crack. The likelihood of diagonal cracking in the slab can be influenced by a number of factors, such as: the moment-shear ratio; the geometry of the profiled steel sheeting; the orientation of sheeting ribs; and the slab reinforcement.

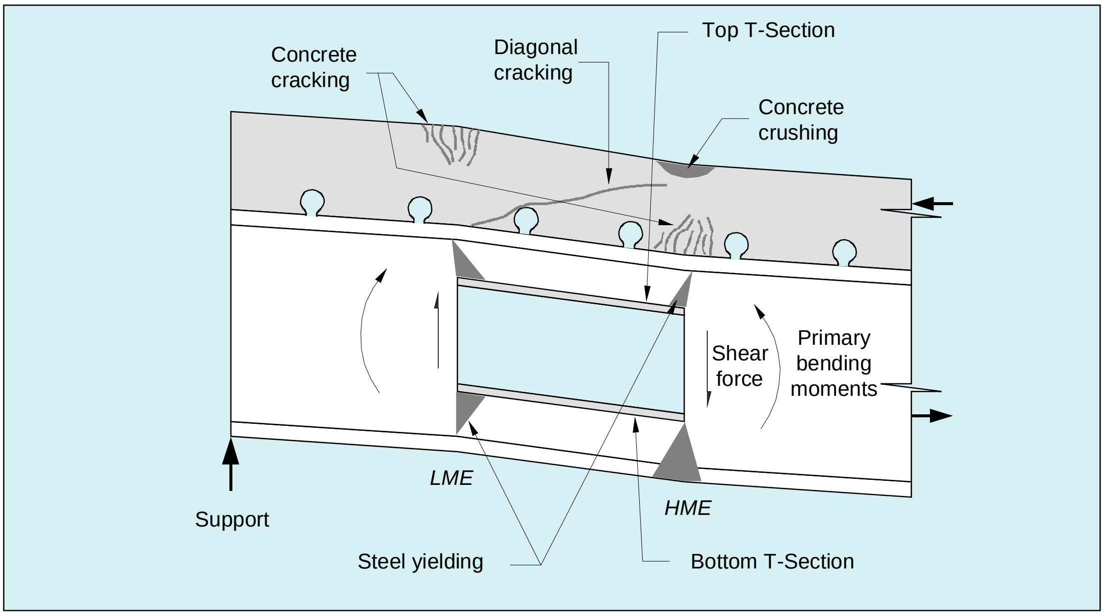


Figure 3.1 Behaviour at Ultimate Load

When the sheeting ribs are orientated perpendicular to the longitudinal axis of the steel beam, the diagonal crack initiates at the top of the ribs and rapidly propagates through the cover slab causing failure. Tests show that the behaviour of a composite beam with the sheeting laid perpendicular to the steel beam can be significantly improved if the width of this crack is controlled using special steel reinforcement in the concrete slab [13]. This steel reinforcement was originally developed to prevent rib shearing failure in composite edge beams [16,17,19], and is now commercially available as DECKMESH [12].

Primary and Secondary Bending Moments

The existence of primary and secondary bending moments in the region of a large web penetration is illustrated in Figure 3.2.

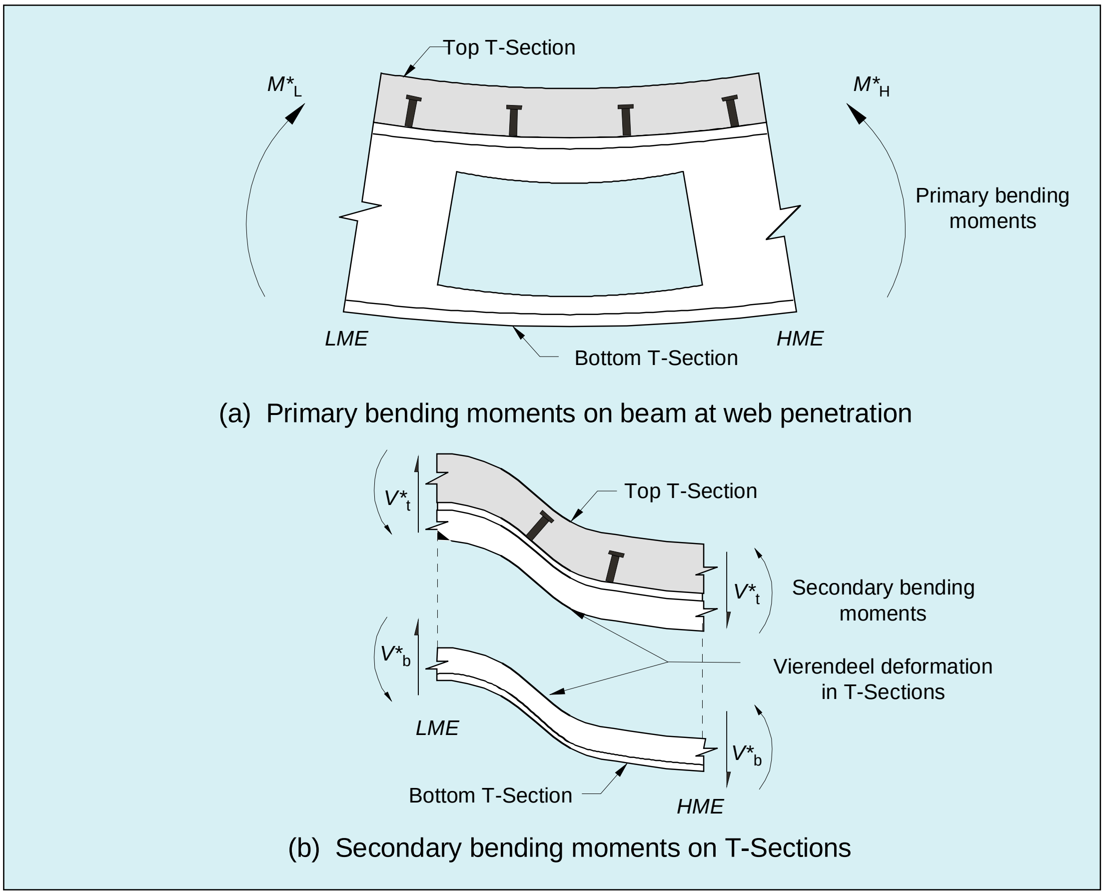


Figure 3.2 Primary and Secondary Bending Moments in the Region of a Web Penetration

Effect of Web Penetrations on Maximum Compressive Force in Concrete Flange

In a simply-supported composite beam, the maximum compressive force that can develop in the concrete flange at any particular cross-section can be governed by various factors such as the strength and distribution of the shear connectors, the tensile capacity of the steel section, the compressive strength of the concrete, etc. When a web penetration is incorporated in the steel beam, this can reduce the compressive force that can develop in the concrete flange at some of the other cross-sections of the composite beam, as shown in Fig. 3.3 (where it is assumed that the shear connector distribution remains unchanged after the introduction of the web penetration, and that they are uniformly spaced). Design rules to cater for this situation are given in Clause 6.6 of AS 2327.1.

Design Moment Capacity

The design moment capacity at the web penetration is calculated at the *HME*, in accordance with the requirements of AS 2327.1, while accounting for:

(a) the depth of the penetration;

(b) any horizontal reinforcement at the top and bottom edges of the penetration; and

(c) the degree of shear connection (β) at the *HME* of the penetration.

The effect of vertical shear force is ignored, and therefore, so are secondary bending moments arising from Vierendeel action.

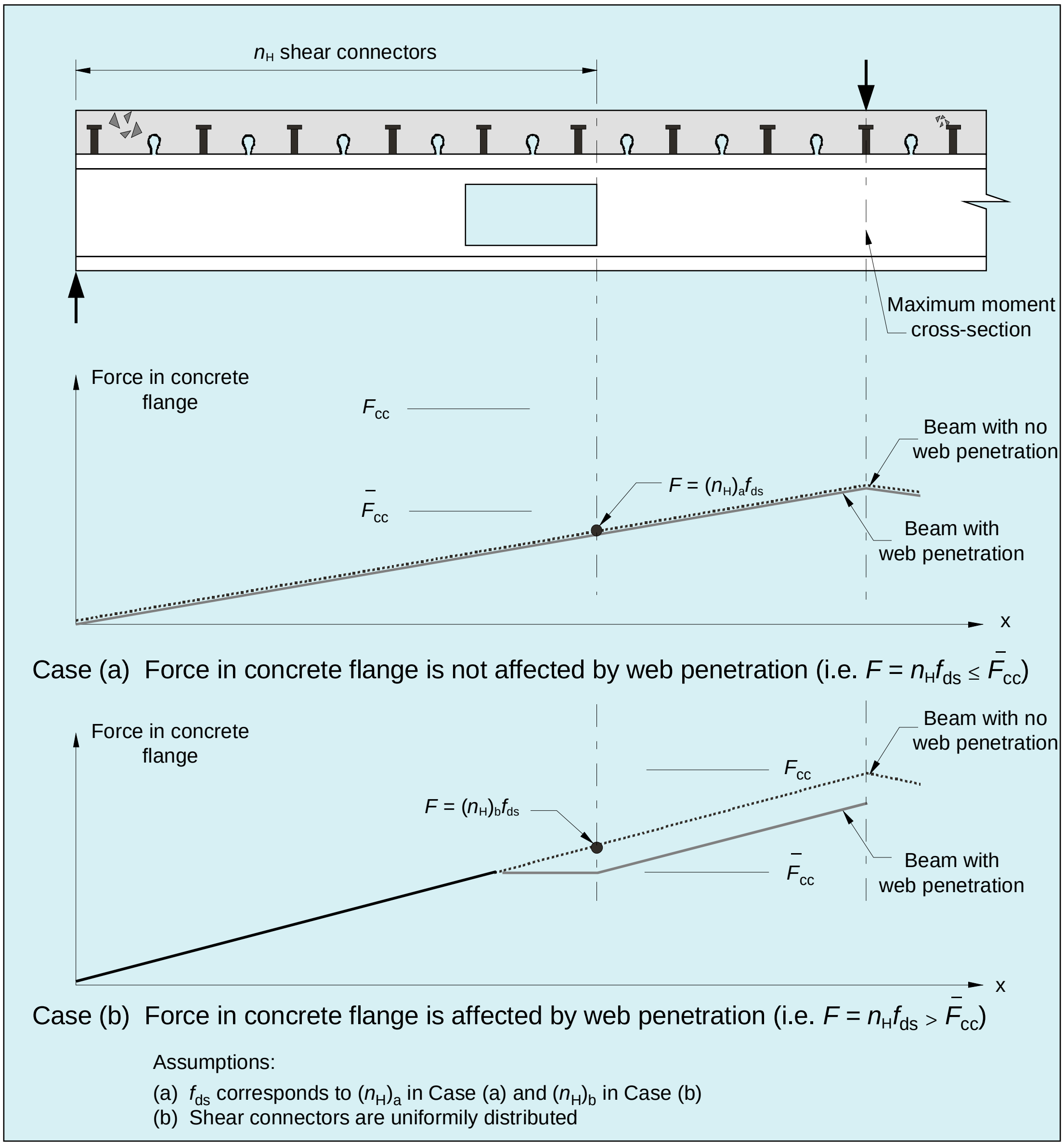


Figure 3.3 Influence of Web Penetration on Maximum Compressive Force in Concrete Flange

Design Vertical Shear Capacity

In the case of composite beams without large web penetrations designed in accordance with AS 2327.1, it is assumed that the shear force is resisted by the steel beam alone when calculating the design vertical shear capacity. This simplifying assumption is considered too conservative at cross-sections within a web penetration when a significant portion of the steel web has been removed. It is assumed that the concrete slab also contributes to the design shear capacity of the composite beam, if the combined design shear capacity of the top and bottom steel T-sections is insufficient to resist the design vertical shear force.

The model used to determine the nominal vertical shear capacity of a composite beam in the region of a web penetration is presented in Section 4.2.

Moment-Shear Interaction

In accordance with the strength design method given in AS 2327.1, the nominal moment capacity of a cross-section of a composite beam without a web penetration is assumed to be affected by shear when the shear ratio, γ, is greater than 0.5 (see Clause 6.4 of AS 2327.1). In this case, the nominal moment capacity is assumed to reduce linearly with the shear ratio until the entire steel web is fully utilised resisting shear, and hence makes no contribution to moment capacity. When $\gamma = 1.0$, the only contribution to the moment capacity from the steel section is due to the steel flanges. The resulting tri-linear moment-shear interaction curve is shown in Fig. D3.2 of AS 2327.1.

It should be noted that a different moment-shear interaction relationship, defined by a continuous cubic equation, as shown in Fig. 4.1, is adopted in the web penetration design method. This same moment-shear interaction equation is used by ASCE Task Committee [4], Redwood and Cho [8] and Oehlers and Bradford [10].

Penetration Reinforcement

There are numerous ways of reinforcing web penetrations to minimise the loss of strength and stiffness that can arise due to their presence. Some of these reinforcing arrangements are shown in Fig. 3.4. However, the strength design formulae given in Section 6 have been derived assuming the steel plate or flat bar reinforcement is continuously welded to the web, as close as practicable to the top and bottom horizontal edges of the penetration. Therefore, only the reinforcement arrangements shown in Fig. 3.4(a) are valid for use with this document.

3.2 Deflection Calculation

The method given in this booklet can be used to calculate the total deflection of a simply-supported bare steel or composite beam incorporating a large web penetration.

Basis of Calculation for Composite Beam

The method requires the following two deflection components to be calculated and added together to obtain the total deflection of a composite beam:

(a) total deflection of the beam with no web penetration, calculated in accordance with the simplified method given in AS 2327.1; plus the

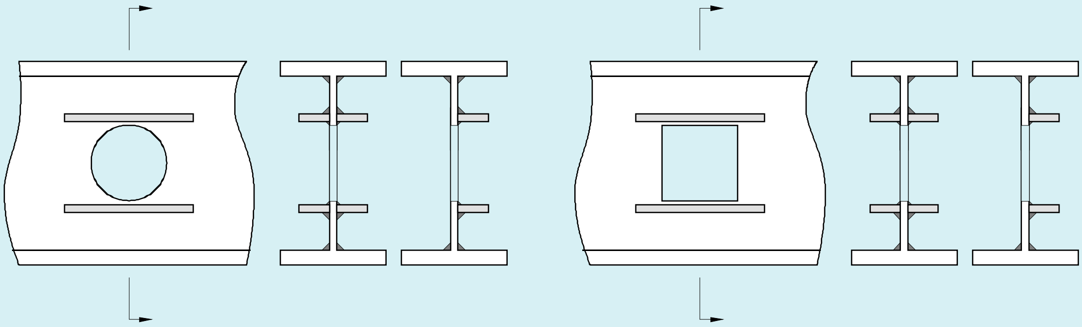
(b) additional deflection due to the presence of the web penetration.

The simplified method given in AS 2327.1 accounts for the effects of long- and short-term loading and partial shear connection. The additional deflection component due to the presence of the penetration can be calculated for both long- and short-term loading conditions. The second moments of area of the T-sections required for this calculation are determined ignoring the effects of partial shear connection.

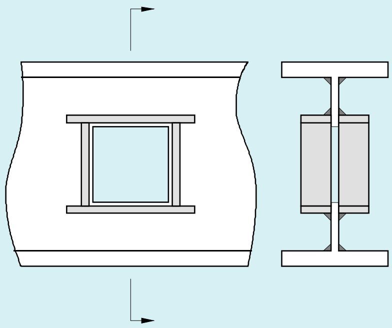
In calculating the additional deflection component in (b), the bending, shear and Vierendeel deformations within the length of the penetration are taken into account, and the remaining parts of the beam on either side of the penetration are assumed to be two rigid arms. These rigid arms are assumed to undergo no deformation, but their rotations contribute to the deflection of the beam.

The method assumes linear elastic behaviour and hence does not account for deflections due to plastic or buckling deformations in any part of the beam. Concrete shrinkage and creep effects are accounted for separately.

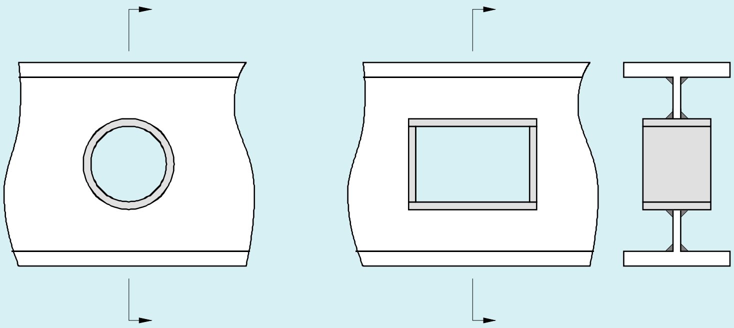
The additional deflection for a beam with multiple penetrations can be obtained by summing the additional elastic deflections due to the individual penetrations.



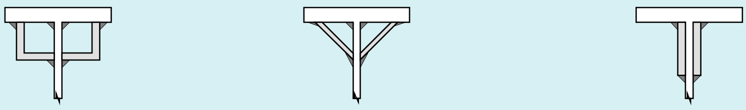
(a) Horizontal reinforcement welded to web



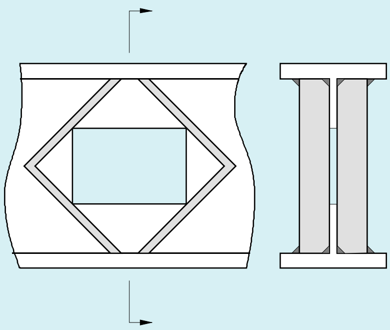
(b) Horizontal and vertical reinforcement welded to web



(c) Penetration edge reinforced with flats



(d) T-Sections strengthened



(e) Diagonal reinforcement

Note: The design method is applicable for penetrations with reinforcement arrangement (a) only.

Figure 3.4 Arrangements of Web Penetration Reinforcement

Design of Simply-Supported Composite Beams with Large Web Penetrations

Design Booklet DB1.3

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Disclaimer

Foreword

OneSteel is a leading manufacturer of steel long products in Australia after its spin-off from BHP Pty Ltd on the 1st November 2000. It manufactures a wide range of steel products, including structural, rail, rod, bar, wire, pipe and tube products and markets welded beams.

OneSteel is committed to providing to design engineers, technical information and design tools to assist with the use, design and specification of its products. This design booklet "Design of Simply-Supported Beams with Large Web Penetrations" was the third design booklet of the Composite Structures Design Manual, which is now being completed and maintained by OneSteel.

The initial development work required to produce the design booklets was carried out at BHP Melbourne Research Laboratories before its closure in May 1998. OneSteel Market Mills is funding the University of Western Sydney's Centre for Construction Technology and Research in continuing the research and development work to publish this and future booklets.

The Composite Structures Design Manual refers specifically to the range of long products that are manufactured by OneSteel and plate products that continue to be manufactured by BHP. It is strongly recommended that OneSteel sections and reinforcement and BHP plate products are specified for construction when any of the design models in the design booklets are used, as the models and design formulae including product tolerances, mechanical properties and chemical composition have been validated by detailed structural testing using only OneSteel and BHP products.

To ensure that the Designer's intent is met, it is recommended that a note to this effect be included in the design documentation.

Contents

Preface

This design booklet forms part of a suite of booklets covering the design of simply-supported and continuous composite beams, composite slabs, composite columns, steel and composite connections and related topics. The booklets are part of the OneSteel Market Mills' Composite Structures Design Manual which has been produced to foster composite steel-frame building construction in Australia to ensure cost-competitive building solutions for specifiers, builders and developers.

The additional design information necessary to allow large web penetrations to be incorporated into simply-supported bare steel and composite beams is presented in this booklet. Design issues with respect to strength and deflection control are addressed. The non-composite bare steel state arises during construction prior to the concrete hardening.

Large rectangular and circular penetrations are often made in the steel web of composite beams for the passage of horizontal building services. This allows the plenum height to be reduced when using economical, standard UB and WB steel sections. However, large penetrations weaken a composite beam locally and reduce its overall flexural stiffness, and therefore their effect must be considered in design.

Neither the Steel Structures Standard AS 4100 nor the Composite Beam Standard AS 2327.1 contains design provisions for large web penetrations. The rules provided in the booklet for designing bare steel beams with large penetrations are compatible with AS 4100. For the composite state, the rules are compatible with AS 2327.1, and have been proposed as an acceptable method of design to be referred to in Amendment No. 1 of this Standard expected to be published this year.

Information is also given to assist design engineers to understand the engineering principles on which the design methods are based. This includes:

(a) explanatory information on important concepts and models;

(b) the limits of application of the methods; and

(c) worked examples.

Design capacity tables are given in Appendix C to simplify the strength design process. The information provided can be used to design for either the bare steel or composite states. The tables cover a range of situations involving 300PLUS® UB and WB steel sections supporting a composite slab and incorporating large web penetrations. A spreadsheet program named WEBPEN™ is available to assist with the strength design calculations.

Although these design aids are intended to make the design process more efficient, it is essential that the user obtain a clear understanding of the basis of the design rules and the design approach by working through this document and the relevant parts of associated design Standards such as AS 4100 and AS 2327.1.