**American Railway Engineering and Maintenance-of-Way Association**
**Ballot**

1. **Committee and Subcommittee: 8**
2. **Ballot Number: 08-22-02**
3. **Assignment:** Edits to Part 2 – Shear Strength
4. **Ballot Item:**
5. **Rationale:**

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**Note to Publisher – ADD THIS LINE TO 2.2.1 Notations**

$d_{dh}$ = depth of entire composite section, inches (mm). See Section 2.29.5 and Section 2.35.5

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# SECTION 2.29 SHEAR

## 2.29.1 SHEAR STRESS (20232005) R(2022))

a. Design shear stress v shall be computed by:

$$v = \frac{V}{b_w d}$$

**EQ 2-14**

where:

V = design shear force at section considered

$b_w$ = the width of web

d = the distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement.

For a circular section, $b_w$ shall be taken as the diameter and d need not be less than the distance from the extreme compression fiber to the centroid of the longitudinal reinforcement in the opposite half of the member or may shall be taken as 0.8 times the diameter of the section.

b. When the reaction in the direction of the applied shear introduces compression into the end region of the member, sections located less than a distance d from the face of the support may be designed for the same shear force Vv as that computed at a distance d. An exception occurs when major concentrated loads are imposed between that point and the face of support. In that case, sections closer than d to the support shall be designed for V at distance d plus the major concentrated loads.

c. Shear stress carried by concrete, $v_c$, shall be calculated according to Article 2.29.2. When v exceeds $v_c$, shear reinforcement shall be provided according to Article 2.29.3. Whenever applicable, the effects of torsion shall be added.

d. For tapered webs, $b_w$ shall be the average width or 1.2 times the minimum width, whichever is smaller.

## 2.29.2 PERMISSIBLE SHEAR STRESS (20232005) R(2022))

**NOTE:** The value of $\sqrt{f'_c}$ used in computing $v_c$ in this paragraph shall not be taken greater than 100 psi (0.69 MPa).

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a. Shear stress carried by concrete, $v_c$ shall not exceed $0.95\sqrt{f'_c}$ (or $0.079\sqrt{f'_c}$ in metric) unless a more detailed analysis is made in accordance with Article 2.29.2b or Article 2.29.2c. For members subject to axial tension, $v_c$ shall not exceed the value given in Article 2.29.2d. For lightweight concrete, the provisions of Article 2.29.2f shall apply.

b. Shear stress carried by concrete, $v_c$, for members subject to shear and flexure only, may be computed by:

$$v_c = 0.9\sqrt{f'_c} + 1100\rho_w\frac{Vd}{M}$$

**EQ 2-15**

$$v_c = 0.075\sqrt{f'_c} + 7.58\rho_w\frac{Vd}{M}$$

**EQ 2-15M**

but $v_c$ shall not exceed $1.6\sqrt{f'_c}$ (or $0.13\sqrt{f'_c}$ in metric). The quantity $\frac{Vd}{M}$ shall not be taken greater than 1.0, where M is the design moment occurring simultaneously with V at the section considered.

c. For members subject to axial compression, $v_c$ may be computed by:

$$v_c = 0.9\left(1 + \frac{0.0006N}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-16**

$$v_c = 10.8\left(0.0069 + \frac{0.0006N}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-16M**

The quantity $\frac{N}{A_g}$ shall be expressed in psi (MPa).

d. For members subject to significant axial tension, shear reinforcement shall be designed to carry the total shear, unless a more detailed analysis is made using:

$$v_c = 0.9\left(1 + \frac{0.004N}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-17**

$$v_c = 10.8\left(0.0069 + \frac{0.004N}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-17M**

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where:

N is negative for tension

The quantity $\frac{N}{A_g}$ shall be expressed in psi (MPa).

e. Special provisions for slabs of box culverts. For slabs of box culverts under rail with 18 inches (450 mm)~~2 feet (600 mm)~~ or more of fill (base of rail to top of culvert), shear stress $v_c$ may be computed by:

$$v_c = \sqrt{f'_c} + 2200\rho\frac{Vd}{M}$$

**EQ 2-18**

$$v_c = 0.083\sqrt{f'_c} + 15.2\rho\frac{Vd}{M}$$

**EQ 2-18M**

but $v_c$ shall not exceed $1.8\sqrt{f'_c}$ (or $0.15\sqrt{f'_c}$ in metric). For single cell box culverts only, $v_c$ need not be taken less than $1.4\sqrt{f'_c}$ (or $0.12\sqrt{f'_c}$ in metric) for slabs monolithic with walls or $1.2\sqrt{f'_c}$ (or $0.10\sqrt{f'_c}$ in metric) for slabs simply supported. The quantity of $\frac{Vd}{M}$ shall not be taken greater than 1.0, where M is the moment occurring simultaneously with V at the section considered.

f. The provisions for shear stress, $v_c$ carried by concrete apply to normal weight concrete. When lightweight aggregate concretes ~~are~~ is used~~, one of~~ the following modifications shall apply:

When $f_{ct}$ is specified, shear stress $v_c$ shall be multiplied by the concrete density modification factor, λ, determined as:

$$\lambda = \frac{f_{ct}}{6.7\sqrt{f'_c}} \leq 1.0 \quad \text{or} \quad (\lambda = 1.8\frac{f_{ct}}{\sqrt{f'_c}} \leq 1.0 \quad \text{Metric})$$

When $f_{ct}$ is not specified, shear stress $v_c$ shall be multiplied by the concrete density modification factor, λ, determined as:

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$$0.75 \leq \lambda \;= 0.0075w_c \;\leq 1.0 \;\text{ or }\; (0.75 \leq \lambda \;= 0.000468w_c \;\leq 1.0 \;\text{ Metric})$$

(1) modified by substituting $f_{ct}/6.7$ (or 1.8 $f_{ct}$ in metric) for $\sqrt{f'_c}$ but the value of $f_{ct}/6.7$ (or 1.8 $f_{ct}$ in metric) used shall not $\sqrt{f'_c}$.

(2) When $f_{ct}$ is not specified, shear stress $v_c$ shall be multiplied by 0.85.

### 2.29.3 DESIGN OF SHEAR REINFORCEMENT (2023005) R(2022)

Shear reinforcement shall conform to the general requirements of Section 2.10.

a. Shear reinforcement shall conform to the general requirements of Section 2.10. When shear reinforcement perpendicular to the axis of the member is used, required area shall be computed by:

$$A_v = \frac{(v - v_c)b_w s}{f_s}$$

**EQ 2-19**

b. When inclined stirrups or bent bars are used as shear reinforcement the following provisions apply:

(1) When inclined stirrups are used, required area shall be computed by:

$$A_v = \frac{(v - v_c)b_w s}{f_s(\sin\alpha + \cos\alpha)}$$

**EQ 2-20**

(2) When shear reinforcement consists of a single bar or a single group of parallel bars, all bent up at the same distance from the support, required area shall be computed by:

$$A_v = \frac{(v - v_c)b_w d}{f_s \sin\alpha}$$

**EQ 2-21**

in which $(v - v_c)$ shall not exceed $1.5\sqrt{f'_c}$ (or $0.12\sqrt{f'_c}$ in metric).

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(3) When shear reinforcement consists of a series of parallel bent-up bars or groups of parallel bent-up bars at different distances from the support, required area shall be computed by Article 2.29.3b(1).

(4) Only the center three-fourths of the inclined portion of any longitudinal bar that is bent shall be considered effective for shear reinforcement.

c. Where more than one type of shear reinforcement is used to reinforce the same portion of the member, required area shall be computed as the sum for the various types separately. No one type shall resist more than 2/3 of the total shear resisted by reinforcement. In such computations, $v_c$ shall be included only once.

d. When $(v - v_c)$ exceeds $2\sqrt{f'_c}$ (or $0.17\sqrt{f'_c}$ in metric), maximum spacings given in Article 2.10.3 shall be reduced by one-half.

e. The value of $(v - v_c)$ shall not exceed $4\sqrt{f'_c}$ (or $0.33\sqrt{f'_c}$ in metric).

f. When flexural reinforcement located within the width of a member used to compute the shear strength is terminated in a tension zone, shear reinforcement shall be provided in accordance with Article 2.13.1g.

## 2.29.4 SHEAR-FRICTION (2023005) R(2022)

a. Provisions for shear-friction are to be applied where it is appropriate to consider shear transfer across a given plane, such as: an existing or potential crack, an interface between dissimilar materials, or an interface between two concretes cast at different times.

b. A crack shall be assumed to occur along the shear plane considered. Required area of shear-friction reinforcement, $A_{vf}$ across the shear plane may be designed using either Article 2.29.4c or any other shear transfer design methods that result in prediction of strength in substantial agreement with results of comprehensive tests. Provisions of Article 2.29.4d through Article 2.29.4h shall apply for all calculations of shear transfer strength.

c. Shear-friction design method.

(1) Shear-friction reinforcement is perpendicular to shear plane, area of shear-friction reinforcement $A_{vf}$ shall be computed by:

$$A_{vf} = \frac{V}{f_s \mu}$$

**EQ 2-22**

where:

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$\mu$ = the coefficient of friction in accordance with Article 2.29.4c(3).

(2) When shear-friction reinforcement is inclined to shear plane such that the shear force produces tension in shear-friction reinforcement, area of shear-friction reinforcement $A_{vf}$ shall be computed by:

$$A_{vf} = \frac{V}{f_s(\mu \sin\alpha_f + \cos\alpha_f)}$$

**EQ 2-23**

where:

$\alpha_f$ = angle between shear-friction reinforcement and shear plane.

**EQ 2-23**

(3) Coefficient of friction $\mu$ in **EQ 2-22** and **EQ 2-23** shall be

concrete placed monolithically ........ $1.4\lambda$

concrete placed against hardened concrete with surface intentionally roughened as specified in Article 2.29.4g ........ $1.0\lambda$

concrete placed against hardened concrete not intentionally roughened ........ $0.6\lambda$

concrete anchored to as-rolled structural steel by headed studs or by reinforcing bars (see Article 2.29.4h) ........ $0.7\lambda$

where:

$\lambda$ = 1.0 for normal weight concrete
$\lambda$ = ~~and~~ 0.85 for sand-lightweight concrete
$\lambda$ = 0.75 for all other lightweight concrete.

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d. Shear stress v on area of concrete section resisting shear transfer shall not exceed 0.09 $f'_c$ nor 360 psi (2.5 MPa).

e. Net tension across shear plane shall be resisted by additional reinforcement. Permanent net compression across shear plane may be taken as additive to the force in the shear-friction reinforcement $A_{vf}f_s$, when calculating required $A_{vf}$.

f. Shear-friction reinforcement shall be appropriately placed along the shear plane and shall be anchored to develop the specified yield strength on both sides by embedment, hooks, studs or welding to special devices.

g. For the purpose of Article 2.29.4, when concrete is placed against previously hardened concrete, the interface for shear transfer shall be clean and free of laitance. If $\mu$ is assumed equal to $1.0\lambda$, interface shall be roughened to a full amplitude of approximately 0.25 inches (6 mm).

h. When shear is transferred between as-rolled steel and concrete using headed studs or welded reinforcing bars, steel shall be clean and free of paint.

## 2.29.5 HORIZONTAL SHEAR DESIGN FOR COMPOSITE CONCRETE FLEXURAL MEMBERS (2023~~005) R(2022~~)

a. In a composite member, full transfer of horizontal shear forces shall be assured at contact surfaces of interconnected elements.

b. Design of cross sections subject to horizontal shear may be in accordance with provisions of Article 2.29.5c or Article 2.29.5d, or any other shear transfer design method that results in prediction of strength in substantial agreement with results of comprehensive tests.

c. Design horizontal shear stress, $v_{dh}$ at any cross section may be computed by:

~~$v_{dh} = \frac{V}{b_w d}$~~ $$v_{dh} = \frac{V}{b_w \; d_{dh}}$$

**EQ 2-24**

where:

V = design shear force at section considered

$d_{dh}$ = depth of entire composite section

$b_w$ = the width of web

Horizontal shear, $v_{dh}$ shall not exceed permissible horizontal shear $v_h$ in accordance with the following:

(1) When contact surface is clean, free of laitance, and intentionally roughened, shear stress $v_h$ shall not exceed 36 psi (0.25 MPa).

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(2) When minimum ties are provided in accordance with Article 2.29.5e, and contact surface is clean and free of laitance, but not intentionally roughened, shear stress $v_h$ shall not exceed 36 psi (0.25 MPa).

(3) When minimum ties are provided in accordance with Article 2.29.5e, and contact surface is clean, free of laitance, and intentionally roughened to a full amplitude of approximately 1/4 inch (6 mm), shear stress $v_h$ shall not exceed 160 psi (1.1 MPa).

(4) For each percent of tie reinforcement crossing the contact surface in excess of the minimum required by Article 2.29.5e, permissible $v_h$ may be increased by $72f_y/40{,}000$ psi (or $72f_y/280$ MPa in metric).

d. Horizontal shear may be investigated by computing, in any segment not exceeding one-tenth of the span, the actual change in compressive or tensile force, and provisions made to transfer that force as horizontal shear between interconnected elements. Horizontal shear shall not exceed the permissible horizontal shear stress $v_h$ in accordance with Article 2.29.5c.

e. Ties for horizontal shear.

(1) When required, aA minimum area of tie reinforcement shall be provided between interconnected elements. Tie area shall not be less than $50b_ws/f_y$ (or $0.35b_ws/f_y$ in metric), and tie spacing ‘s’ shall not exceed 4 times the least web width of support element, nor 24 inches (600 mm).

(2) Ties for horizontal shear may consist of single bars or wire, multiple leg stirrups, or vertical legs of welded wire fabric (smooth or deformed). All ties shall be adequately anchored into interconnected elements by embedment or hooks.

(3) All beam shear reinforcement shall extend into cast-in-place deck slabs. Extended shear reinforcement may be used in satisfying the minimum tie reinforcement.

## 2.29.6 SPECIAL PROVISIONS FOR SLABS AND FOOTINGS (2023005) R(2022)

a. Shear capacity of slabs and footings in the vicinity of concentrated loads or reactions shall be governed by the more severe of two conditions:

(1) The slab or footing acting as a wide beam, with a critical section extending in a plane across the entire width and located at a distance d from the face of the concentrated load or reaction area. For this condition, the slab or footing shall be designed in accordance with Article 2.29.1 through Article 2.29.3.

(2) Two-way action for the slab or footing, with a critical section perpendicular to the plane of the slab and located so that its perimeter, $b_o$, is a minimum and approaches no closer than d/2 to the perimeter of the concentrated load or reaction area. For this condition, the slab or footing shall be designed in accordance with Article 2.29.6b and Article 2.29.6c.

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(3) At footings supported on piles the shear on the critical section shall be determined in accordance with:

(a) Entire reaction from any pile whose center is located $d_p/2$ or more outside the critical section shall be considered as producing shear on that section.

(b) Reaction from any pile whose center is located $d_p/2$ or more inside the critical section shall be considered as producing no shear on that section.

(c) For intermediate positions of pile center, the portion of the pile reaction to be considered as producing shear on the critical section shall be based on linear interpolation between full value at $d_p/2$ outside the section and zero value at $d_p/2$ inside the section.

b. Design shear stress for two-way action shall be computed by:

$$v = \frac{V}{b_o d}$$

**EQ 2-25**

where:

V and $b_o$ are taken at the critical section defined in Article 2.29.6a(2).

$$v_c = \left(0.8 + \frac{2}{\beta_c}\right)\sqrt{f'_c}$$ ; $f'_c$ in psi **EQ 2-26**

c. Design shear v shall not exceed the smallest $v_c$ given by **EQ 2-26** or **EQ 2-27** unless shear reinforcement is provided in accordance with Article 2.29.6d.

$$v_c = \left(0.8 + \frac{2}{\beta_c}\right)\sqrt{f'_c}$$ ; $f'_c$ in psi **EQ 2-26**

**EQ 2-26M**

$$v_c = \left(0.066 + \frac{0.17}{\beta_c}\right)\sqrt{f'_c}$$ ;$f'_c$ in MPa

or

**EQ 2-27**

$$v_c = \left(0.8 + \frac{\alpha_s d}{b_o}\right)\sqrt{f'_c}$$ ;$f'_c$ in psi

$$v_c = \left(0.8 + \frac{\alpha_s d}{b_o}\right)\frac{\sqrt{f'_c}}{12}$$ **EQ 2-27M**

;$f'_c$ in MPa

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but not greater than $1.8\sqrt{f'_c}$ (or $0.15\sqrt{f'_c}$ in metric).

where:

$\beta_c$ is the ratio of long side to short side of concentrated load or reaction area.

where:

$\alpha_s$ is 20 for interior concentrated loads or reaction areas, 15 for edge concentrated loads or reaction areas and 10 for corner concentrated loads or reaction areas.

d. If shear reinforcement consisting of bars or wires is provided in accordance with Article 2.29.3, $v_c$ at any section shall not exceed $0.9\sqrt{f'_c}$ (or $0.075\sqrt{f'_c}$ in metric) and v shall not exceed $3\sqrt{f'_c}$ (or $0.25\sqrt{f'_c}$ in metric). Shear stresses shall be investigated at the critical section defined in Article 2.29.6a(2) and at successive sections more distant from the support.

## 2.29.7 SPECIAL PROVISIONS FOR BRACKETS AND CORBELS (2023005) R(2022)

a. The following provisions shall apply to brackets and corbels with a shear span-to-depth ratio $a_v/d$ not greater than unity, and subject to a horizontal tensile force $N_c$ not larger than V. Distance d shall be measured at face of support.

b. Depth at outside edge of bearing area shall not be less than 0.5d.

c. Section at face of support shall be designed to resist simultaneously a shear V, a moment [$Va_v + N_c(h-d)$], and a horizontal tensile force $N_c$. Distance d shall be measured at the face of support.

(1) Design of shear-friction reinforcement $A_{vf}$ to resist shear V shall be in accordance with Article 2.29.4. For normal weight concrete, shear stress v shall not exceed $0.09f'_c$ nor 360 psi (2.5 MPa). For "sand-lightweight" concrete, shear stress v shall not exceed $(0.09 – 0.03a_v/d)f'_c$ nor $(360 – 126a_v/d)$ psi (or ($2.5 – 0.09a_v/d$) MPa in metric).

(2) Reinforcement $A_f$ to resist moment [$Va_v + N_c(h-d)$] shall be computed in accordance with Section 2.26 and Section 2.27.

(3) Reinforcement $A_n$ to resist tensile force $N_c$ shall be computed by $A_n = N_c/f_s$. Tensile force $N_c$ shall not be taken less than 0.2V unless special provisions are made to avoid tensile forces.

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(4) Area of primary tension reinforcement $A_s$ shall be made equal to the greater of ($A_f + A_n$), or ($2A_{vf}/3 + A_n$).

d. Closed stirrups or ties parallel to $A_s$, with a total area $A_h$ not less than 0.5 ($A_s – A_n$), shall be uniformly distributed within two-thirds of the effective depth adjacent to $A_s$.

e. Ratio $\rho = A_s/bd$ shall not be taken less than 0.04 ($f'_c/f_y$).

f. At front face of bracket or corbel, primary tension reinforcement $A_s$ shall be anchored by one of the following:

(1) a structural weld to a transverse bar of at least equal size; weld to be designed to develop specified yield strength $f_y$ of $A_s$ bars;

(2) bending primary tension bars $A_s$ back to form a horizontal loop, or

(3) some other means of positive anchorage.

g. Bearing area of load on bracket or corbel shall not project beyond straight portion of primary tension bars $A_s$, nor project beyond interior face of transverse anchor bar (if one is provided).

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## SECTION 2.35 SHEAR

### 2.35.1 SHEAR STRENGTH (2023~~005~~) ~~R(2022)~~

a. Factored shear stress $v_u$ shall be computed by:

$$v_u = \frac{V_u}{\Phi b_w d}$$

**EQ 2-45**

where:

$b_w$ = the width of web

$d$ = the distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement

For a circular section, $b_w$ shall be taken as the diameter, and d need not be taken less than the distance from the extreme compression fiber to the centroid of the longitudinal reinforcement in the opposite half of the member or may shall be taken as 0.8 times the diameter of the section.

b. When the reaction in the direction of the applied shear introduces compression into the end region of the member and loads are applied at or near the top of the member, sections located less than a distance d from the face of the support may be designed for the same shear $v_u$ as that computed at a distance d. An exception occurs when major concentrated loads are imposed between that point and the face of support. In that case sections closer than d to the support shall be designed for $V_u$ at distance d plus the major concentrated loads.

c. Shear stress carried by concrete, $v_c$, shall be calculated according to Article 2.35.2. When $v_u$ exceeds $v_c$, shear reinforcement shall be provided according to Article 2.35.3. Whenever applicable, the effects of torsion shall be added.

**NOTE:** The design criteria for combined shear and torsion given in "Building Code Requirements for Reinforced Concrete – ACI318-02" may be used.

d. For tapered webs, $b_w$ shall be the average width or 1.2 times the minimum width, whichever is smaller.

## 2.35.2 PERMISSIBLE SHEAR STRESS (2023010) R(2022)

**NOTE:** The value $f'_c$ used in computing $v_c$ shall not be taken greater than 10,000 psi (69 MPa).

a. Shear stress carried by concrete, $v_c$ shall not exceed $2\sqrt{f'_c}$ (or $0.17\sqrt{f'_c}$ in metric) unless a more detailed analysis is made in accordance with Article 2.35.2b or Article 2.35.2c. For members subject to axial tension, $v_c$ shall not exceed the value given in Article 2.35.2d. For lightweight concrete, the provisions of Article 2.35.2f shall apply.

b. Shear stress carried by concrete, $v_c$, for members subject to shear and flexure only, may be computed by:

$$v_c = 1.9\sqrt{f'_c} + 2500\rho_w \frac{V_u d}{M_u}$$

**EQ 2-46**

$$v_c = 0.16\sqrt{f'_c} + 17\rho_w \frac{V_u d}{M_u}$$

**EQ 2-46M**

but $v_c$ shall not exceed $3.5\sqrt{f'_c}$ (or $0.29\sqrt{f'_c}$ in metric). The quantity $\frac{V_u d}{M_u}$ shall not be taken greater than 1.0, where $M_u$ is the factored moment occurring simultaneously with $V_u$ at the section considered.

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c. For members subject to axial compression, $v_c$ may be computed by:

**EQ 2-47**

$$v_c = 2\left(1 + 0.0005\frac{N_u}{A_g}\right)\sqrt{f'_c}$$

$$v_c = 0.17\left(1 + 0.072\frac{N_u}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-47M**

The quantity $\frac{N_u}{A_g}$ shall be expressed in psi (MPa).

d. For members subject to significant axial tension, shear reinforcement shall be designed to carry the total shear, unless a more detailed analysis is made using

$$v_c = 2\left(1 + 0.002\frac{N_u}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-48**

$$v_c = 0.17\left(1 + 0.29\frac{N_u}{A_g}\right)\sqrt{f'_c}$$

**EQ 2-48M**

where:

$N_u$ is negative for tension

the quantity $\frac{N_u}{A_g}$ shall be expressed in psi (MPa).

e. Special provisions for slabs of box culverts. For slabs of box culverts under rail with 18 inches (450 mm)~~2 feet (600 mm)~~ or more of fill (base of rail to top of culvert), shear stress $v_c$ may be computed by:

$$v_c = 2.14\sqrt{f'_c} + 4600\rho\frac{V_u d}{M_u}$$

**EQ 2-49**

$$v_c = 0.18\sqrt{f'_c} + 32\rho\frac{V_u d}{M_u}$$

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**EQ 2-49M**

but $v_c$ shall not exceed $4\sqrt{f'_c}$ (or $\frac{1}{3}\sqrt{f'_c}$ in metric). For single cell box culverts only, $v_c$ need not be taken less than $3\sqrt{f'_c}$ (or $\frac{\sqrt{f'_c}}{4}$ in metric) for slabs monolithic with walls or $2.5\sqrt{f'_c}$ (or $\frac{5}{24}\sqrt{f'_c}$ in metric) for slabs simply supported. The quantity $\frac{V_u d}{M_u}$ shall not be taken greater than 1.0, where $M_u$ is factored moment occurring simultaneously with $V_u$ at section considered.

f. The provisions for shear stress, $v_c$ carried by concrete apply to normal weight concrete. When lightweight aggregate concrete are is used, one of the following modifications shall apply:

(1) When $f_{ct}$ is specified, shear stress $v_c$ shall be modified by substituting $f_{ct}$/6.7(of 1.8$f_{ct}$ in metric) for $\sqrt{f'_c}$, but the value of $f_{ct}$/6.7 (of 1.8 $f_{ct}$ in metric) used shall not exceed $\sqrt{f'_c}$.

(2) When $f_{ct}$ is not specified, shear stress $v_c$ shall be multiplied by 0.85 for sand-lightweight concrete.

When $f_{ct}$ is specified, shear stress $v_c$ shall be multiplied by the concrete density modification factor, λ, determined as:

$$\lambda = \frac{f_{ct}}{6.7\sqrt{f'_c}} \leq 1.0 \quad \text{or} \quad \left(\lambda = 1.8\frac{f_{ct}}{\sqrt{f'_c}} \leq 1.0 \quad \text{Metric}\right)$$

When $f_{ct}$ is not specified, shear stress $v_c$ shall be multiplied by the concrete density modification factor, λ, determined as:

$$0.75 \leq \lambda = 0.0075 w_c \leq 1.0 \quad \text{or} \quad (0.75 \leq \lambda = 0.000468 w_c \leq 1.0 \quad \text{Metric})$$

## 2.35.3 DESIGN OF SHEAR REINFORCEMENT (2023005) R(2022)

Shear reinforcement shall conform to the general requirements of Section 2.10.

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a. ~~Shear reinforcement shall conform to the general requirements of Section 2.10.~~ When shear reinforcement perpendicular to the axis of the member is used, required area shall be computed by:

$$A_v = \frac{(v_u - v_c)b_w s}{f_y}$$

**EQ 2-50**

b. When inclined stirrups or bent bars are used as shear reinforcement the following provisions apply:

(1) When inclined stirrups are used, required area shall be computed by:

$$A_v = \frac{(v_u - v_c)b_w s}{f_y(\sin\alpha + \cos\alpha)}$$

**EQ 2-51**

(2) When shear reinforcement consists of a single bar or a single group of parallel bars, all bent up at the same distance from the support, required area shall be computed by:

$$A_v = \frac{(v_u - v_c)b_w d}{f_y \sin\alpha}$$

**EQ 2-52**

in which $(v_u - v_c)$ shall not exceed $3\sqrt{f'_c}$ (or $\frac{\sqrt{f'_c}}{4}$ in metric).

(3) When shear reinforcement consists of a series of parallel bent-up bars or groups of parallel bent-up bars at different distances from the support, required area shall be computed using Article 2.35.3b(1).

(4) Only the center three-fourths of the inclined portion of any one longitudinal bar that is bent shall be considered effective for shear reinforcement.

c. When more than one type of shear reinforcement is used to reinforce the same portion of the member, required area shall be computed as the sum for the various types separately. No one type shall resist more than 2/3 of the total shear resisted by reinforcement. In such computations, $v_c$ shall be included only once.

d. When $(v_u - v_c)$ exceeds $4\sqrt{f'_c}$ (or $\frac{\sqrt{f'_c}}{3}$ in metric), maximum spacings given in Article 2.10.3 shall be reduced by one-half.

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e. The value of $(v_u - v_c)$ shall not exceed $8\sqrt{f'_c}$ (or $\frac{2\sqrt{f'_c}}{3}$ in metric).

f. When flexural reinforcement located within the width of a member used to compute the shear strength is terminated in a tension zone, shear reinforcement shall be provided in accordance with Article 2.13.1g.

## 2.35.4 SHEAR-FRICTION (2023005) R(2022)

a. Provisions for shear-friction are to be applied where it is appropriate to consider shear transfer across a given plane, such as: an existing or potential crack, an interface between dissimilar materials, or an interface between two concretes cast at different times.

b. A crack shall be assumed to occur along the shear plane considered. Required area of shear-friction reinforcement $A_{vf}$ across the shear plane may be designed using either Article 2.35.4c or any other shear transfer design method that results in prediction of strength in substantial agreement with results of comprehensive tests. Provisions of Article 2.35.4d through Article 2.35.4h shall apply for all calculations of shear transfer strength.

c. Shear-friction design method.

(1) When shear-friction reinforcement is perpendicular to shear plane, area of shear-friction reinforcement $A_{vf}$ shall be computed by:

$$A_{vf} = \frac{V_u}{\phi f_y \mu}$$

**EQ 2-53**

where:

$\mu$ = the coefficient of friction in accordance with Article 2.35.4c(3).

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(2) When shear-friction reinforcement is inclined to shear plane such that the shear force produces tension in shear-friction reinforcement, area of shear friction reinforcement $A_{vf}$ shall be computed by:

$$A_{vf} = \frac{V_u}{\phi f_y(\mu \sin\alpha_f + \cos\alpha_f)}$$

**EQ 2-54**

where:

$\alpha_f$ = angle between shear-friction reinforcement and shear plane

**EQ 2-54**

(3) Coefficient of friction $\mu$ in **EQ 2-53** and **EQ 2-54** shall be:

concrete placed monolithically .......................................................................... $1.4\lambda$

concrete placed against hardened concrete with surface intentionally roughened as specified in Article 2.35.4g ............................................. $1.0\lambda$

concrete placed against hardened concrete not intentionally roughened ................. $0.6\lambda$

concrete anchored to as-rolled structural steel by headed studs or by reinforcing bars (see Article 2.35.4h) ........................................................................ $0.7\lambda$

where:

$\lambda$ = 1.0 for normal weight concrete ~~and~~

$\lambda$ = 0.85 for sand-lightweight concrete~~.~~

$\lambda$ = 0.75 for all other lightweight concrete.

d. Shear stress $v_u$ on area of concrete section resisting shear transfer shall not exceed $0.2f'_c$ nor 800 psi (5.5 MPa).

e. Net tension across shear plane shall be resisted by additional reinforcement. Permanent net compression across shear plane may be taken as additive to the force in the shear-friction reinforcement $A_{vf}f_y$, when calculating required $A_{vf}$.

f. Shear-friction reinforcement shall be appropriately placed along the shear plane and shall be anchored to develop the specified yield strength on both sides by embedment, hooks, studs or welding to special devices.

g. For the purpose of this paragraph, when concrete is placed against previously hardened concrete, the interface for shear transfer shall be clean and free of laitance. If $\mu$ is assumed equal to $1.0\lambda$, interface shall be roughened to a full amplitude of approximately 1/4 inch (6 mm).

h. When shear is transferred between as-rolled steel and concrete using headed studs or welded reinforcing bars, steel shall be clean and free of paint.

## 2.35.5 HORIZONTAL SHEAR DESIGN FOR COMPOSITE CONCRETE FLEXURAL MEMBERS (2023~~005~~) ~~R(2022)~~

a. In a composite member, full transfer of horizontal shear forces shall be assured at contact surfaces of interconnected elements.

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b. Design of cross sections subject to horizontal shear may be in accordance with provisions of Article 2.35.5c or Article 2.35.5d, or any other shear transfer design method that results in prediction of strength in substantial agreement with results of comprehensive tests.

c. Design horizontal shear stress, $v_{uh}$ at any cross section may be computed by:

$$v_{uh} = \frac{V_u}{\phi b_v d}$$

$$v_{uh} = \frac{V_u}{\Phi b_v \ d_{dh}}$$

**EQ 2-55**

where:

$V_u$ = factored shear force at section considered

$d_{dh}$ = depth of entire composite section

$b_v$ = width of cross section being investigated for horizontal shear

Horizontal shear, $v_{uh}$ shall not exceed permissible horizontal shear $v_h$ in accordance with the following:

(1) When contact surface is clean, free of laitance, and intentionally roughened, shear stress $v_h$ shall not exceed 80 psi (0.55 MPa).

(2) When minimum ties are provided in accordance with Article 2.35.5e, and contact surface is clean and free of laitance, but not intentionally roughened, shear stress $v_h$ shall not exceed 80 psi (0.55 MPa).

(3) When ties are provided in accordance with Article 2.35.5e and contact surfaces are clean, free of laitance and intentionally roughened to a full amplitude of 1/4 inch (6 mm), shear stress, $v_h$, shall be taken equal to $(260 + 0.6\rho_v f_y)\lambda$ in psi $[(1.8 + 0.6\rho_v f_y)\lambda$ in MPa]; but not greater than 500 psi (3.5 MPa).

(4) When factored shear stress, $v_u$, at section considered exceeds $\phi$ 500 psi ($\phi$ 3.5 in MPa), design for horizontal shear shall be in accordance with Shear-Friction (2023.

d. Horizontal shear may be investigated by computing, in any segment not exceeding one-tenth of the span, the actual change in compressive or tensile force to be transferred, and provisions made to transfer that force as horizontal shear between interconnected elements. The factored horizontal shear stress shall not exceed the horizontal shear strength $v_{uh}$ in accordance with Article 2.35.5c, except that length of segment considered shall be substituted for d.

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e. Ties for horizontal shear.

(1) When required, a ~~A~~ minimum area of tie reinforcement shall be provided between interconnected elements. Tie area shall not be less than $50b_ws/f_y$ (or $0.35b_ws/f_y$ in metric), and tie spacing s shall not exceed 4 times the least web width of support element, nor 24 inches (600 mm).

(2) Ties for horizontal shear may consist of single bars or wire, multiple leg stirrups, or vertical legs of welded wire fabric (smooth or deformed). All ties shall be adequately anchored into interconnected elements by embedment or hooks.

(3) All beam shear reinforcement shall extend into cast-in-place deck slabs. Extended shear reinforcement may be used in satisfying the minimum tie reinforcement.

## 2.35.6 SPECIAL PROVISIONS FOR SLABS AND FOOTINGS (2023~~005) R(2022~~)

a. Shear strength of slabs and footings in the vicinity of concentrated loads or reactions shall be governed by the more severe of the following conditions:

(1) The slab or footing acting as a wide beam, with a critical section extending in a plane across the entire width and located at a distance d from the face of the concentrated load or reaction area. For this condition, the slab or footing shall be designed in accordance with Article 2.35.1 through Article 2.35.3.

(2) Two-way action for the slab or footing, with a critical section perpendicular to the plane of the slab and located so that its perimeter, $b_o$, is a minimum and approaches no closer than d/2 to the perimeter of the concentrated load or reaction area. For this condition, the slab or footing shall be designed in accordance with Article 2.35.6b and Article 2.35.6c.

(3) For footings supported on piles the shear on the critical section shall be determined in accordance with:

(a) Entire reaction from any pile whose center is located $d_p/2$ or more outside the critical section shall be considered as producing shear on that section.

(b) Reaction from any pile whose center is located $d_p/2$ or more inside the critical section shall be considered as producing no shear on that section.

(c) For intermediate positions of pile center, the portion of the pile reaction to be considered as producing shear on the critical section shall be based on linear interpolation between full value at $d_p/2$ outside the section and zero value at $d_p/2$ inside the section.

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b. Factored shear stress for two-way action shall be computed by:

**EQ 2-56**

$$v_u = \frac{V_u}{\Phi b_o d}$$

where:

$V_u$ and $b_o$ = are taken at the critical section defined in Article 2.35.6a(2).

**EQ 2-59**

c. Factored shear stress $v_u$ shall not exceed the minimum $v_c$ given by **EQ 2-57**, **EQ 5-58** and **EQ 2-59** unless shear reinforcement is provided in accordance with Article 2.35.6d.

$$v_c = \left(\frac{\alpha_s d}{b_o} + 2\right)\sqrt{f'_c}$$

**EQ 2-57**

$$v_c = \left(\frac{\alpha_s d}{b_o} + 2\right)\frac{\sqrt{f'_c}}{12}$$

**EQ 2-57M**

$$v_c = \left(2 + \frac{4}{\beta_c}\right)\sqrt{f'_c}$$

**EQ 2-58**

$$v_c = \left(1 + \frac{2}{\beta_c}\right)\frac{\sqrt{f'_c}}{6}$$

**EQ 2-58M**

$$v_c = 4\sqrt{f'_c}$$

**EQ 2-59**

$$v_c = \frac{1}{3}\sqrt{f'_c}$$

**EQ 2-59M**

$\beta_c$ is the ratio of long side to short side of concentrated load or reaction area. $\alpha_s$ is 40 for interior concentrated loads or reaction areas, 30 for edge concentrated loads or reaction areas, and 20 for corner concentrated loads or reaction areas.

d. If shear reinforcement consisting of bars or wires is provided in accordance with Article 2.35.3, $v_c$ at any section shall not exceed $2\sqrt{f'_c}$ (or $\frac{1}{6}\sqrt{f'_c}$ in metric) and $v_u$ shall not exceed $6\sqrt{f'_c}$ (or $\frac{1}{2}\sqrt{f'_c}$ in metric). Shear stresses shall be investigated at the critical section defined in Article 2.35.6a(2) and at successive sections more distant from the support.

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## 2.35.7 SPECIAL PROVISIONS FOR BRACKETS AND CORBELS (2023005) R(2022)

a. The following provisions shall apply to brackets and corbels with a shear span-to-depth ratio and $a_v/d$ not greater than unity, and subject to a horizontal tensile force $N_{uc}$ not larger than $V_u$. Distance d shall be measured at face of support.

b. Depth at outside edge of bearing area shall not be less than 0.5d.

c. Section at face of support shall be designed to resist simultaneously a shear $V_u$, a moment $[V_u a_v + N_{uc}(h - d)]$, and a horizontal tensile force $N_{uc}$.

(1) In all design calculations in accordance with this paragraph, strength reduction factor $\phi$ shall be taken equal to 0.85.

(2) Design of shear-friction reinforcement $A_{vf}$ to resist shear $V_u$ shall be in accordance with Article 2.35.4. For normal weight concrete, shear stress $v_u$ shall not exceed 0.2 $f'_c$ nor 800 psi (5.5 MPa). For "sand-lightweight" concrete, shear stress $v_u$ shall not exceed $(0.2 - 0.07a_v/d)\, f'_c$ nor $(800 - 280a_v/d)$ psi $(5.5 - 1.9a_v/d$ MPa).

(3) Reinforcement $A_f$ to resist moment $[V_u a_v + N_{uc}(h - d)]$ shall be computed in accordance with Section 2.31 and Section 2.32.

(4) Reinforcement $A_n$ to resist tensile force $N_{uc}$ shall be computed by $A_n = N_{uc}/\phi f_y$. Tensile force $N_{uc}$ shall not be taken less than $0.2V_u$ unless special provisions are made to avoid tensile forces.

(5) Area of primary tension reinforcement $A_s$ shall be made equal to the greater of $(A_f + A_n)$, or $(2A_{vf}/3 + A_n)$.

d. Closed stirrups or ties parallel to $A_s$, with a total area of $A_h$ not less than $0.5(A_s - A_n)$, shall be uniformly distributed within two-thirds of the effective depth adjacent to $A_s$.

e. Ratio $\rho = A_s/bd$ shall not be taken less than $0.04\,(f'_c/f_y)$.

f. At front face of bracket or corbel, primary tension reinforcement $A_s$ shall be anchored by one of the following:

(1) a structural weld to a transverse bar of at least equal size; weld to be designed to develop specified yield strength $f_y$ of $A_s$ bars;

(2) bending primary tension bars $A_s$ back to form a horizontalcontinuous loop, or

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(3) some other means of positive anchorage.

g. Bearing area of load on bracket or corbel shall not project beyond straight portion of primary tension bars $A_s$, nor project beyond interior face of transverse anchor bar (if one is provided).

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